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CLIMATIC CYCLES AND TREE-GROWTH

A STUDY OF THE ANNUAL RINGS OF TREES IN RELATION TO CLIMATE AND SOLAR ACTIVITY

BY

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I. INTRODUCTION.

The investigation described in the subsequent pages bears close relation to three sciences. It was approached by the author from the standpoint of astronomy and a desire to understand the variations of the sun. It was hoped that these variations could be more accurately studied by correlation with climatic phenomena. But the science of meteorology is still comparatively new and supplies us only with a few decades of records on which to base our conclusions. So botanical aid was sought in order to extend our knowledge of weather changes over hundreds and even thousands of years by making use of the dependence of the annual rings of trees in dry climates on the annual rainfall. If the relationship sought proves to be real, the rings in the trunks of trees give us not only a means of studying climatic changes through long periods of years, but perhaps also of tracing changes in solar activity during the same time. Thus astronomy, meteorology, and botany join in a study to which each contributes essential parts and from which, it is hoped, each may gain a small measure of benefit.

It is entirely natural that the yellow pine, *Pinus ponderosa*, common on the western Rockies, should have been the first tree studied, since it was an intimate and extensive acquaintance with the forest and with the climate of northern Arizona that led the writer to the thought of possible relation between the two. The climate had been sought for astronomical reasons because its limited rainfall of about 22 inches gave many clear nights and superb skies. The forest with its great extent and stately trees proved wonderfully attractive and the absence of undergrowth or of other species of trees was its most noticeable feature to anyone accustomed to moist climates. Evidently the absence of undergrowth was related to the dryness, and the critical problem of the tree was to survive periods of drought rather than to compete successfully with other species in the struggle to obtain food supply. The following argument, therefore, was naturally suggested: (1) the rings of trees measure the growth; (2) growth depends largely upon the amount of moisture, especially in a climate where the quantity of moisture is limited; (3) in such countries, therefore, the rings are likely to form a measure of precipitation. Relationship to temperature and other weather elements may be very important, but precipitation was thought to be the controlling factor in this region and for the sake of simplicity it is the element fundamentally considered throughout the present study.

In the very beginning of the work it was expected that only in large averages would a relationship be found between tree-growth and climate. Accordingly, something like 10,000 measures had been made on the pines of northern Arizona and the results all tabulated, when it occurred to the writer to compare the annual growth of Flagstaff trees directly with the 8 or 10 years of rainfall records taken at the United States Weather Bureau station recently established there. It was immediately seen that the accuracy with which tree-growth as shown in the rings may represent annual rainfall was far greater than anticipated. In a considerable number of cases, but especially in the dry-climate groups, this has been found to be in the neighborhood of 70 per cent, which is raised substantially by applying a formula to allow for some degree of moisture conservation. At the present time, therefore, it is possible to lay a foundation for this study directly in the fact that the rings of trees form an approximate measure of the rainfall.

When the studies were carried to northern Europe an equal exactness in following the rainfall was not found, but a direct correlation was discovered between tree-growth and solar activity. Subsequent groups have been obtained from moist regions of the United States, and one is led to believe that this altered reaction is a question of precipitation and that it must be kept well in mind in any application of the methods hereafter described.

Since the beginning of this investigation, in 1901, assistance has been received from several sources which it is a pleasure to acknowledge at this time. Mr. T. A. Riordian, of Flagstaff, had 24 sections of the early Flagstaff group cut from the ends of logs and shipped to me. Mr. Willard P. Steel assisted in the measuring of the first 25 sections and a number of friends helped in the tabulation. Mr. C. H. Hinderer, of the United States Forest Service, at Prescott, Arizona, assisted in procuring the Prescott groups. Mr. H. S. Graves, Chief of the United States Forest Service, gave me several letters of introduction to foresters in Europe, by which I was greatly assisted in procuring the 9 European groups. I am glad to express my obligation to Dr. H. H. Jelstrup of Christiania, Professor Gunnar Schotte of Stockholm, Professor Dr. A. Schwappach of Eberswalde, and Professor A. Cieslar of Vienna, for especial aid in this connection. Assistance in completing the Vermont group was given by Mr. M. H. Douglass and others, and for aid in procuring the Oregon group I am glad to mention the excellent work of Mr. Robert H. Weitknecht, who was for a time connected with the United States Forest Service at Portland, Oregon. I am indebted to Mr. George A. Hume, of the Sanger Lumber Company, for important help in connection with the sequoia groups. In 1914 a grant of $200 was received from the Elizabeth Thompson Science Fund for study upon the correlation between tree-growth and solar variation. In 1918 a fund of $250 was placed at my disposal by the American Association for the Advancement of Science. This was for the purpose of extending the sequoia ring-record from 2,200 years in length (the result of preceding collection) to 3,000 years. This material was collected in

the summer of 1918 and the measurements and tabulation finished soon after. I wish gratefully to acknowledge the courtesy of the editors of the Astrophysical Journal and the Bulletin of the American Geographical Society for permission to use illustrations and extracts from articles of mine which they have published. Plate 9 and figure 31 in the text are from the former journal. Thanks are also extended to Professor Ellsworth Huntington for the use of several text-figures which first appeared in my chapter of his work (1914).

TREES SUITABLE FOR CLIMATIC STUDY.

During the course of this investigation the wood and growth of numerous species of trees have been examined with reference to their adaptability to the purposes herein described. The collections visited include several in London, especially one in the South Kensington Museum, fossils in the Jermyn Street Museum, the lumber-yards of Messrs. W. W. Howard Bros. & Company, tree sections and fossils in the geological museum at Berlin, fossils in the lignite beds of Grube Ilsa near Dresden, and fossils chiefly in Munich and Vienna. In

TABLE 1.—*List of trees in the Jessup collection whose rings were counted.*

Scientific name.	Common name.	Locality.	Approximate center, A. D.	Possible periods.	Quality of ring sequence.
Pinus torreyana	Torrey pine	San Diego, Cal.	1790	11 years	
Pinus radiata	Monterey pine	Monterey, Cal.	1855	22 years	
Pinus monticola	Western white pine.	Oregon	1641	11 years; Brückner.	
Pinus strobiformis	Mexican white pine.	Southern Arizona.	1706	22 years	
Pinus strobus	White pine	Nova Scotia	1740?	22 years; Brückner.	Fair.
Pinus tæda	Loblolly pine	Florida	1731		
Pinus echinata	Short-leaved pine.	Missouri	1650		
Tsuga heterophylla.	Western hemlock	Canada northwest coast.	1700	Uncertain	
Tsuga caroliniana	Carolina hemlock	Carolina	1697	Poor, 22 yr.; Brückner.	Good.
Tsuga canadensis	Canadian hemlock	Nova Scotia	1525	11 years; Brückner.	Good.
Pseudotsuga macrocarpa.	Bigcone fir	Southern California.	1480?	11 years	Good.
Pseudotsuga mucronata.	Douglas fir	Oregon	1315	11 years	Good.
Picea sitchensis	Tideland spruce	Northwest coast	1798		Very good.
Picea rubens	Red spruce	Nova Scotia	1610		
Sequoia gigantea	Bigtree	California	550	Brückner	Good.
Taxodium distichum.	Bald cypress	Florida	1670?		
Cupressus macnabiana.	Macnab cypress	Northern California.	1760		Very good.
Toxylon pomiferum.	Osage orange	Southern Arkansas.	1765		Fair.
Ulmus fulva	Slippery elm	Missouri	1770	20 years	

America, collections were examined at the Smithsonian Institution in Washington, the horticultural exhibit at the Panama-Pacific Exposition in 1915, the museum at Chicago, but especially the Jessup collection in the American Museum of Natural History in New York City. Much careful counting of rings was done at the latter.[1]

Considering all the trees examined, the conclusion was reached that the conifers, by the great regions they cover, the great variety of climates they endure, and especially by the prominence of their rings, seem best adapted to the purpose in hand. The chief trees, used with approximate number of rings measured in each, are: the yellow pine (*Pinus ponderosa*) about 14,000; Scotch pine (*P. silvestris*) about 9,000; hemlock (*Tsuga canadensis*) 2,500; Douglas fir (*Pseudotsuga mucronata*) 2,500; sequoia (*Sequoia gigantea*) 47,000.

INTRODUCTION TO SPECIAL STUDIES ON THE YELLOW PINE.

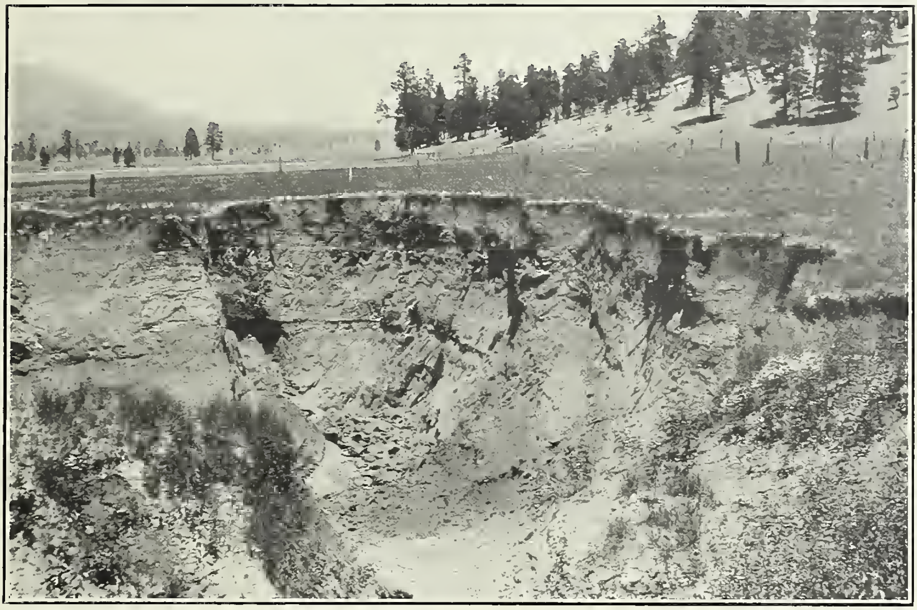
Before taking up the details of collection and measurement it is desirable to describe certain preliminary studies, such as those upon the yearly identity of the rings, time of the year of ring formation, and so forth. These studies were made chiefly upon the yellow pine of northern Arizona, but from the similarity between the pine and the other trees used it seems safe to say that the results apply equally to the Scotch pine, sequoia, hemlock and other species employed.

Location.—The yellow pines upon which the studies were made were obtained near Flagstaff, in the central part of northern Arizona, at an elevation of about 6,800 feet above the sea. The northern part of the State is largely a plateau forming the southern extension of the great Colorado Plateau. This high area is intersected some 65 miles north of Flagstaff by the Grand Canyon of the Colorado River. South of the town the high elevation extends 50 to 75 miles, varying only a few hundred feet from place to place, and then falls away abruptly at the "Rim." Oak Creek Canyon begins some 10 miles south of Flagstaff and flows to the south into the Verde River. The general drainage nearer town is gently to the northeast into the Little Colorado River some 40 miles away. Ten miles north of town the plateau culminates in the San Francisco Peaks, which reach an elevation of 12,700 feet. This mountain is a finely shaped volcanic mass with the old crater breaking away into a canyon toward the northeast. The town is in latitude 35° N. and longitude 113° W., and lies between two ancient lava streams 200 to 400 feet in height. It has a "wash" flowing through it from north to south, but this carries water only in time of severe storm or of rapidly melting snow.

---

[1] The 17-foot section of sequoia was reviewed with some care and the dates on it checked. The dating is well done, as the errors are mostly under 15 years. The rings are large an do not show marked variations in width. Much repair work has been done on it, and the pieces of wood filling the drying cracks near the year 800 A. D. almost completely interrupt the continuity of the rings.

A



B

A. Bottomless pits near Flagstaff, illustrating drainage through limestone.
B. Yellow pine forest of northern Arizona.

The general country rock is Kaibab limestone in horizontal layers forming the plateau, surmounted by lavas over extensive areas near the mountain. The bedrock is covered by a thin soil, largely formed in place. The soil over the limestones is porous, while that over the lavas has much clay and holds water. There is no swampy ground and therefore no conservation of moisture from year to year. Consequently variations in moisture-supply are quickly felt by the trees. The pine forest is remarkable for the absence of other kinds of vegetation. It covers all parts of the plateau from about 5,000 feet in elevation to about 9,000. At the lower edge of the pine forest a belt of cedars, smaller than the pines and round in shape and with dark-green, thick foliage, makes an attractive landscape.

Climate and seasonal conditions.—The climate follows naturally from the latitude and altitude and the distance from the ocean. In the winters there may be from 1 to 6 feet of snow on the ground at one time. The storms are of the characteristic temperate-zone cyclonic types, but on account of the altitude the preliminary south or east winds are rarely observed. Storms come from the Pacific coast and rain occurs about a day later than in southern California. Spring and autumn are the dry seasons, and the warmest time of year is usually in June, just before the summer rains begin. The summer rains occur in July and August and often come in "spells" that last a week or two, with thunderstorms in the afternoons or at night, followed by clear mornings. Unlike the winter storms, the summer rains are local and apt to be torrential in character, with heavy run-off.

Meteorological records in northern Arizona are necessarily meager, yet not so deficient as might be expected. The country was first settled in the "fifties," when gold was discovered in Arizona as well as in California, and lines of travel were established from Santa Fe westward across the plateau. The "blazings" on the pine trees marking the earlier roads are still to be distinguished. Soon after the opening of the country the government located military camps at various places, and from that time records of rainfall and temperature were kept. The record at Whipple Barracks, near Prescott, begun in 1867, has been continued at Prescott to the present time. It is the longest consecutive record in the pine forest and is therefore used below.

The extreme range in temperature observed in Flagstaff is from about 20° F. below zero to about 100° F. above. But the town is in a peculiarly sheltered position and exhibits much lower night extremes than the "mesas" 200 to 400 feet above it. I have observed a difference of 26° F. between the top and bottom of the hill west of town at sunrise on a winter morning. During the early years of the Lowell Observatory, which is located on the mesa 350 feet above the town, the lower minima were about 5° F. These figures show the conditions to which the trees are subjected.

The unobstructed topography of the plateau where the trees were collected is without doubt a very favorable feature. This leads to very similar conditions for the trees over many miles of country and doubtless greatly assisted in producing concordant tree-records. On the other hand, the San Francisco Peaks, 10 miles north of town, illustrate how meteorological data may vary in rugged localities. The west slopes of these mountains are exposed to the winter westerly storms and have an immense snowfall. Springs abound and all favorable localities are taken up as ranches. East of the mountain, however, the land is dry and barren, and long distances intervene between watering-places.

In a very rugged country like that about Prescott similar differences between east and west mountain slopes must constantly occur. This is the reason of an early difficulty with the Prescott groups. Nearly 60 trees from various localities were measured before a group was found close enough to Prescott to be compared minutely with records of precipitation at that place.

II. PRELIMINARY STUDIES ON THE YELLOW PINE.

YEARLY IDENTITY AND THE DATING OF RINGS.

In comparing the growth of trees with rainfall and other data, it is essential that the date of formation of any individual ring shall be certain. This depends directly on the yearly identity of the rings or the certainty with which one ring and only one is formed each year. The fundamental starting-point in all identification is the ring partially formed at the time of cutting the tree. This is usually found with ease and has led to no uncertainty in the pine. In the sequoia this partial ring is exceedingly soft and had been rubbed off in nearly all trees examined. It was found unmistakably in a tree cut on the date of visit.

Superficial counting of rings is subject to errors due to omission and doubling of rings. In the first investigation of trees at Flagstaff it was supposed that the results were subject to an error of 2 per cent, most of which arose from double rings near the center of the tree. But the discovery and application of the method of cross-identification revolutionized the process of ring identification, and it was proved that the error of unchecked counting in the Arizona pines was 4 per cent and lay almost entirely in the recent years. It was due to the omission of rings or the fusion of several together.

Apart from cross-identification, confidence in the yearly identity of rings comes from the following sources:

(1) Belief that the well-marked seasons of the year cause absolute stoppage of growth in winter. The January mean temperature at Flagstaff is 29° F. and that of July is 65° F.

(2) The known time of cutting of nearly 100 different trees distributed through perhaps a dozen different years successfully and accurately checks cross-identification in the later years of the tree.

(3) The various identifications adopted for recent years check exactly with the neighboring rainfall records in Prescott and other places where such comparison can be made. This will have further illustration in connection with the chapter on rainfall and tree-growth.

(4) A check on the accuracy of the accepted identification of the Flagstaff trees was made by noting every statement of weather, freshets, or crop-failures mentioned by the historian Bancroft in his accounts of the settlements of Arizona and New Mexico. There were 14 cases in which the noted feature of the year agrees with the tree-record to one doubtful disagreement. The most striking correspondences occur with reference to the flood on the Rio Grande in 1680, the famines between 1680 and 1690, and the droughts in Arizona in 1748, 1780, and 1820–23.

The effect of the undetected omission or the doubling of the rings in individual trees is to lessen the intensity of the variations in the curve of growth obtained by the averaging of many trees. The may be divided into two classes: first, local errors of identity in small groups of rings in a few individual trees, which simply flatten the curve without affecting the final count; second, cases in which a given ring, in spite of attempts at cross-identification, is still in doubt, showing clearly in perhaps half of the trees and not in the other half. Such cases affect the final count, but do not flatten the curve. They leave a question of one year in the dating of all the earlier portions of the curve. Only two cases of this latter kind have been noted. One was the year 1822 in the Flagstaff pines (of which there is very little doubt) and the other is the ring 1580 in the sequoias, which was finally decided by material gathered in the special trip of 1919.

CROSS-IDENTIFICATION.

Apart from care in measuring the rings, the details of which will be given in Chapter IV, the most fundamental and essential feature of the method of studying tree-growth is the cross-identification of rings among a group of trees. The ease and accuracy with which this can be done in a fairly homogeneous forest is remarkable. A group of 13 tree sections collected along a distance of a quarter of a mile in the forest of Eberswalde, near Berlin, show almost identical records. Two to ten rings in every decade have enough individuality to make them recognizable in every tree. A group of 12 sections from Central Sweden show such agreement that there is not a single questionable ring in the last 100 years or more. Especially marked combinations of rings can occasionally be traced across Europe between the groups hereafter mentioned. In Arizona the identification across 70 miles of country is unquestioned, and even at 200 miles the resemblance is apparent.

The value and accuracy of cross-identification was first observed in 1911 in connection with the Prescott trees. After measuring the first 18 sections, it became apparent that much the same succession of rings was occurring in each; therefore the other sections were examined and the appearance of some 60 or 70 rings memorized. All the sections were then reviewed and pinpricks placed in each against certain rings which had characteristics common to all. For example, the red ring of 1896 was nearly always double, while the rings of 1884 and 1885 were wider than their neighbors. In the 60 years investigated several obvious details in each decade appeared in every tree. After this success it was evident that the process should be applied to the Flagstaff trees which had been previously collected. Of the 25, however, only 19 had been preserved. A minute comparison was made between these with complete satisfaction. Since then this process has been applied with great care to every group.

After the Flagstaff set was finished, it was compared with the Prescott group. It was interesting to find that the Flagstaff ring records could be identified at once in terms of the rings at Prescott; the narrow ring of 1851 was seen to correspond to one in the Prescott series. The compressed series from 1879 to 1885 likewise had its counterpart at Prescott and formed the portion of the sections which gave the most difficulties in identification. On the whole, so far as can be judged without minute study, the Prescott trees from relatively high elevations approximating the elevation at Flagstaff have a considerably closer resemblance to the Flagstaff sections than do those growing at lower altitudes.

Cross-identification and climate.—The process of cross-identification appears to be applicable to areas far removed from one another, but as the distances increase the resemblances between tree-growth records decrease, due to climatic differences. The correspondence between trees in different regions thus becomes a test of climate and we note a possible field for the application of this process in the delineation of similar climatic areas or meteorological districts. It seems to the author that in this way the growth of vegetation may easily be made of fundamental value in practical meteorology.

MONTH OF BEGINNING ANNUAL MEANS.

It is evident that it must take some time for the transmutation of rain into an important part of the organic tissue. There is evidence, as will be shown later, that the summer rains often have a prompt effect. The winter precipitation, however, is necessarily more remote in its action. Much of the first growth in the spring must come from the melting of the autumn and winter snows. It seems reasonable, therefore, to consider any snowfall as applying to the following yearly ring.

At Flagstaff the precipitation of November is almost always in the form of snow, and therefore that month should certainly be considered as falling after the arboreal New Year of that locality. In view of the uncertainty as to the exact month when the precipitation begins to have an influence upon the growth of the following season, and of probable variations in different years, it seemed wise to test the matter by a purely empirical method. The annual rainfall was ascertained for yearly periods beginning (1) with July 1 of the preceding year, (2) with August 1, and so on to (9) with March 1 of the current year. Another method involved a separating of the summer rains, one-half to apply on each adjacent winter, while a final method involved a similar division of the winter rains. This was done for 12 years at Flagstaff and 43 at Prescott. Part of the Flagstaff curves are given in the lower portion of figure 4, where the rainfall can be compared with the growth of the trees. The curves plotted from these tests were found to have substantial disagreements, although of course the smoothed curves of all of them would be practically identical. A comparison of the growth of the tree with these various curves showed that the use of the year beginning November 1 at Flagstaff and September 1 at Prescott gave the closest agreement between growth and rainfall. At Flagstaff the majority of the trees came from a thin clay soil derived in place from decomposed lava, and so there was little depth for the storage of moisture. At Prescott the sections of group 5, shown in the solid line of figure 7, came from trees growing in a porous soil of decomposed granite in a rather flat depression with reaarded drainage, so that conservation would have a greater influence. Perhaps this explains why the year beginning September 1 gives the best results.

In the region of the great sequoias nearly all the precipitation in the mountains (and quite all in the valleys where comparative rain records are found) comes in the winter months. For these trees, therefore, the winter precipitation is compared with the growth for the succeeding year and the month of beginning annual means is in the autumn.

THE TIME OF YEAR OF RING FORMATION.

Among the problems connected with the relation of the growth of trees and the amount of rainfall, one of the most interesting was suggested by Director R. H. Forbes, formerly of the Arizona Experiment Station. This was to determine the time of formation of the red or autumn portion of the rings and the causes for the formation of double rings, which were very numerous in the Prescott group. It seems evident at once that the growth of red cells is related to the decreased absorption of moisture as winter approaches. A number of tests were made on the Prescott group. The first was designed to determine the character of the rainfall in the years producing double rings. The half-dozen most persistent cases were selected and in each of these the red ring was found double in the following number of cases: 4 out of 10 in 1896; 5 out of 10 in 1891; 7 out of 10 in 1881; 4 out of 10 in 1878, 1872, and 1871. The average width of all the rings was 1.55 mm. The mean rainfall by months for the years above selected was found and is plotted in the solid line of the upper diagram of figure 1. Six other rings showing one double in 10 trees in 1898, but no doubles in 1897, 1885, 1884, 1876, and 1874, and averaging 1.54 mm. in thickness, were then selected and the curve of rainfall by months for the year during which they grew has been plotted as the upper dotted line in figure 1. In each curve the 6 months preceding and the 2 months following the year are included. The curves seem to indicate clearly that the chief cause of doubling is a deficiency of snowfall in the winter months, December to March. This appears to mean that if the winter precipitation is sufficient to bridge over the usual spring drought, the growth continues through the season, giving a large single ring which ends only in the usual red growth as the severity of winter comes on. If, however, the preceding winter precipitation has not been entirely adequate, the spring drought taxes the resources of thetree and some red tissue is formed because of deficient absorption in the early summer before the rains begin. When these rains come the tree continues its growth.

It appears further that if not only the winter snows are lacking, but the spring rains are unusually scanty, then the tree may close up shop for the year and produce its final red tissue in midsummer, gaining no immediate benefit from the summer rains. This appears to be the interpretation of the lower diagram of figure 1. Here the same 6 big doubles mentioned above are plotted, together with a selected list of 6 small singles particularly deficient in red tissues. They are, 1904 double once in 10, 1902 double once in 10, 1899 single, 1895 single, 1894 single, and 1880 double once in 10. In these it is evident that drought in the spring stops the growth of the tree. The double ring, therefore, seems to be an intermediate form between the large normal single ring, growing through the warm parts of the year, and the small, deficient ring, ending its growth by midsummer. This occasional failure to benefit by the summer rains probably explains why the Prescott trees do not show an agreement of more than about 70 per cent between growth and rainfall. It suggests also that the Flagstaff trees, which grow under conditions of more rainfall and have very few double rings, give a more accurate record than those of Prescott.

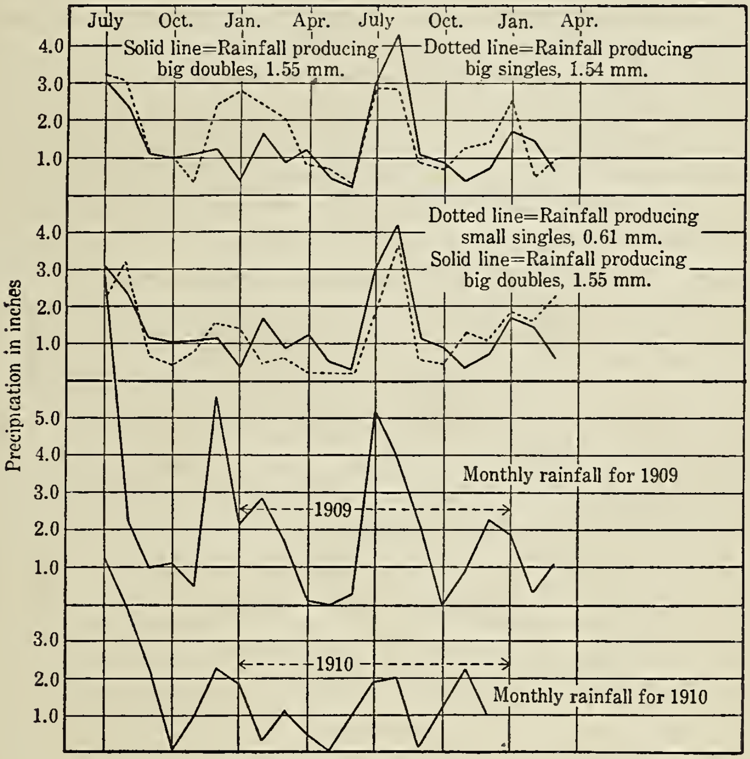


FIG. 1.—Effect of monthly distribution of precipitation on thickness of rings of growth; Prescott, Arizona.

Consistent with this view of the doubling is the condition of the outer ring in the Prescott sections collected by Mr. Hinderer. These trees were cut during various months from May to November. Naturally, those cut in May are in the midst of their most rapid growth, while those cut in summer may or may not show the double ring just forming. The conditions are shown in table 2.

TABLE 2.

Group.	Altitude.	Date of cutting.	Cutting season.	Remarks.
	feet.			
1	6,125	1911	May, June.....	9 out of 10 show white tissue only.
2 and 4	6,420	1909	July to Sept...	30 out of 33 show red ring just forming, probably a doubling.
5	5,800	1909	Summer......	3 or 4 out of 10 show red ring just forming, probably a doubling.
3	6,800	1910	Oct. and Nov.	All 12 show white without red, probably a large single.

By reference to figure 1, showing the curves of monthly rainfall for 1909 and 1910, it will be seen that 1910 would be likely to carry its growth through the year and produce a single line, as in group 3 above. The year 1909 is of intermediate character, having heavy winter precipitation and a severe spring drought of 3 months. In the groups cut at this time 33 out of 43 show a red ring forming in July, August, or September, doubtless the preliminary ring of a double. This lesser red ring is due to the spring drought, and its appearance at this time indicates a lag of a couple of months, more or less, in the response of the tree to rain. The whole matter of the relative thickness of the red and white portions of the rings is illustrated in figure 2. The heavy sinuous line shows the rainfall month by month at Prescott throughout the 43 years under consideration. The total rainfall for the year is indicated by the dotted rectangles while the size and character of the, rings is shown in the solid rectangles. In these the white portion indicates the white tissue and the shaded portion indicates red tissue.

Significance of subdivisions in rings.—The normal ring consists of a soft, light-colored tissue which forms in the spring, merging into a harder reddish portion which abruptly ends as the tree ceases growth for the year. The present subject (namely, the time of year of ring formation) indicates that the red tissue appears as the tree feels lack of sufficient moisture. Therefore, the great diversity in relative size of the red tissue and the occasional appearance of false rings undoubtedly has a real significance as to distribution of precipitation during the growing-season. This subject is a very promising one, but has received little attention in the present work. The trees of the Prescott group offer a few interesting examples of two or three false red rings in one year; they also have exceptionally many cases of omitted rings; both of these peculiarities are explained by the fact that these trees are close to the lowest elevation at which the climate permits them to live; they are therefore greatly affected by rainfall distribution and probably exaggerate its changes.

NUMBER OF TREES NECESSARY FOR RELIABLE RESULTS.

In seeking the best curve of tree-growth which a given locality can supply, it might be thought at first that a very large number of trees must be obtained in order to get an average, but experience has shown that the number may be very small. In order to test the accuracy obtained from a small number of trees, a comparison was made between large groups and small. Of the original 25 trees in the first Flagstaff group, 19 were subjected to very careful cross-identification. Averages were then obtained of the oldest 5, going back about 400 years, the oldest 10 (350 years), the oldest 15 (300 years), and the entire 19 reaching back only 200 years. Finally, the record of the oldest 2 was carried back fully 500 years. On plotting the groups of 15, 10, and 5 with its extension of 2, it became immediately evident that 5 trees gave almost the same growth as 15, even to small details. Between these 5 and the oldest 2 taken by themselves the agreement was not quite so perfect, yet was so close that errors thus introduced would not affect the curves. It must not be taken for granted without test that this remarkable agreement between very small groups of trees is true necessarily for other trees or even for

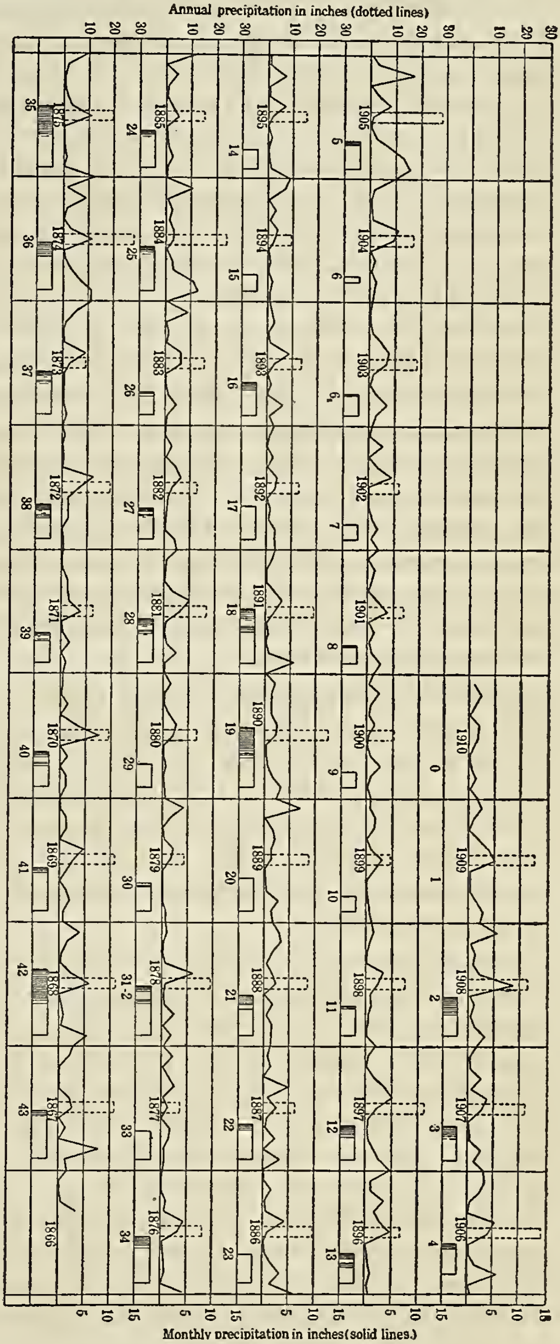


Fig. 2.—Monthly and yearly precipitation at Prescott and size and character of rings.

this yellow pine under all conditions. Without doubt it is here due to homogeneous climatic conditions in a uniform topography and a tree sensitive to varying moisture-supply.

In a good many cases where the number of trees in a group has decreased in earlier years, it has been found (by carrying overlapping curves through a considerable period) that a few trees give essentially the same curves as a large number. From the entire experience I have been led to assign a minimum preferably of 5 trees in any one group, while in some groups (notably the yellow pine of Arizona and the sequoias of California, together with the Scotch pine in central Sweden and in north Germany), 2 trees would give a very excellent record. In only one group have 5 failed to give a satisfactory record, and that was the set of Scotch pines from the outskirts of Christiania. The cross-identification of this group was not felt to be satisfactory, and a double number of trees from that locality would have been an advantage. This failure was thought to be due in part to the rugged character of the region.

Direction of maximum growth.—The maximum trunk-growth was observed to occur a little east of north. The average difference between the radii was 12 per cent. An explanation of this increased growth to the north is to be found in the increased amount of moisture on that side, due to the slower melting of snow and decreased evaporation in the shade. For nearly all these trees the ground had a gentle slope toward the south, so that moisture working down hill reaches the north side of the root system first.

Rate of growth and age.—The relation of average ring-width to radius was found to be intermediate between an inverse proportion to the radius and an inverse proportion to the square of the radius. If the tree merely increased in diameter without growing upward, the width should be roughly inversely proportional to the radius. If the tree is increasing in height at the same time, we should expect an inverse proportion to the square of the radius. We find the relation to be between these.

Growth and soil.—In early studies of 25 yellow pines at Flagstaff it was noticed that a certain subgroup of 6 trees dropped to its strong minima in 1780 and 1880 more promptly than the others. This appears to be connected with the soil upon which the trees grew. This subgroup stood on a limestone formation where the soil is porous and the rock below full of cracks. The other two subgroups grew on recent lavas, very compact and unbroken, covered with a rather thin layer of clayey soil. With the former, therefore, the rain passed quickly through the soil and away, and we do not find so much conservation of moisture as in the latter, where the water could find no convenient outlet. On the whole, the growth seems to be more rapidly influenced by changes of moisture on limestone than on volcanic rocks.

III. COLLECTION OF SECTIONS.

The material upon which the discussion of climatic cycles and tree-growth is based has been derived from 230 trees collected in the 15 years from 1904 to 1918. The regions drawn upon comprise chiefly Arizona with its yellow pine, the Baltic drainage area of north Europe with its Scotch pine, and the high Sierras of California with their great sequoia. Two small collections come respectively from the northeast and northwest coast of the United States. The collections have been made in small, convenient groups as opportunity offered, to each of which a name has been given which will appear below.

The relative dimensions of the various groups may be expressed in terms of the number of measures of rings. In the first Flagstaff group there were about 10,000. In the second Flagstaff group of 1911 only a few hundred. The Prescott groups included about 4,000; the 9 European groups about 9,000. The Vermont group had between 2,500 and 3,000, and the Oregon group about the same. The first collection of sequoias in 1915 had about 25,000 measures and the collection in 1918 embraced about 22,000.

Throughout the whole study it was desired to get as long records as possible and old trees were therefore selected. In nearly every case this meant large trees also. Apart from this no special selection of trees was made at any time, save only in the Christiania group, in which so many of the logs showed a "complacent" habit, with long successions of equal rings rather large in size, that some effort was there made to find the logs which showed variations in ring-size. A complacent ring-record without doubt means that the environment of the trees was well adapted for its best development.

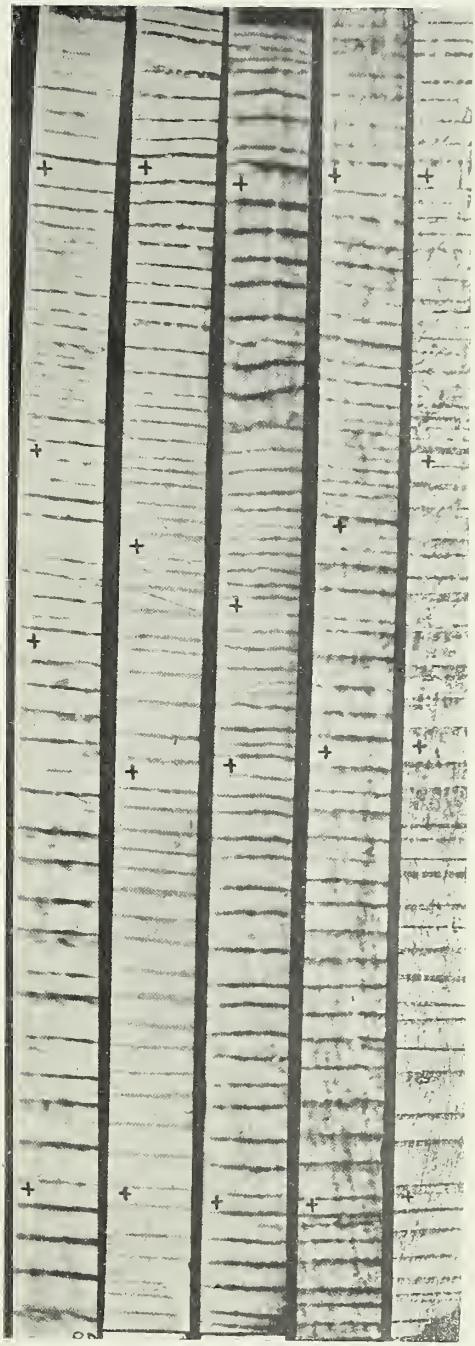
THE FIRST FLAGSTAFF GROUP OF TWENTY-FIVE SECTIONS.

The plan of using tree-rings for the general purpose of a check on astronomical and meteorological phenomena was first formulated in 1901. The first measurements were made in January 1904, on a huge log in the yards of the Arizona Lumber and Timber Company at Flagstaff. This method of measuring was extremely inconvenient and the succeeding 5 sections were cut from logs and sent to town for more careful examination. Hence the exact location of these first 6 was never visited. The remaining 19 trees were selected in 1906 by myself in the forest while the logs were yet lying near their stumps, and I was able to mark on each section the points of the compass and otherwise describe the location. The measurements were completed in 1907 and published in the Monthly Weather Review of June 1909. They had not been subjected to cross-identification and, when the value of this process was recognized in 1911, the 19 sections of which samples had been preserved were compared and a complete cross-identification carried through. Thus the errors of identity in the former tabulation were found (published in 1914[3]) and a complete new set of tables and averages made from the original measures. For a time it was thought that an error of one year might exist in the period of the great drought of 1820–23, but the various checks made upon identity lead easily to the belief that there are no errors of identity in this 500-year series.

Subgroups.—The trees of this group were divided into three subgroups consisting of (1) 6 trees from 3 miles south of Flagstaff; (2) 9 trees from 11 miles southwest of Flagstaff; (3) 10 trees from a point 1 mile west of the last subgroup. A comparison of the 3 subgroups clearly reveals the general character of the longer periods hereafter to be discussed and shows lesser variations to be common to all. Interesting differences, depending on the location in which the trees grew, have been mentioned.

First suggestion of cross-identification.—Other interesting facts came to light. It was especially noticeable that a given year of marked peculiarity could be identified in different trees with surprising ease. This is illustrated in plate 2, where shavings from 5 of the Flagstaff trees have been photographed; the photographs have been enlarged to such a scale that the distance from the large ring 1898 (indicated by the upper line of black crosses) to the small ring 1851 at the lower line of crosses is equal in all cases. The other lines of crosses indicate the noticeably broad rings of 1868 and 1878. An examination of the photographs shows that a very characteristic feature is a group of narrow rings about the years 1879 to 1884. These can be identified in practically every tree and an examination of many stumps which were not measured showed that it was easy to pick them out wherever one chose. Striking verification of this was found in the case of a stump near town which had been cut about 20 years previously. By finding this group of rings, the writer was able to name the year when the tree was felled and the date was verified by the owner of the land. In the more recent work this same group shows conspicuously among Prescott trees, and in general 95 per cent of these trees have rings so characteristically marked that the identification of the same series of rings can be made with little doubt, whether at Flagstaff or at Prescott.

The Flagstaff 500-year record.—Figure 3 shows the Flagstaff tree record from 1385 to 1906 A. D., a period of 522 years. The table of measures from which the curve was plotted will be found on page 112. To give the record from 1503 to 1906, 5 trees are used, and comparisons showed that these 5 gave as accurate a record as a larger number whose inclusion would have shortened the record or made awkward breaks in it. The earlier part of the record is from 2 trees



Cross-identification of rings of growth in yellow pine (*Pinus ponderosa*).

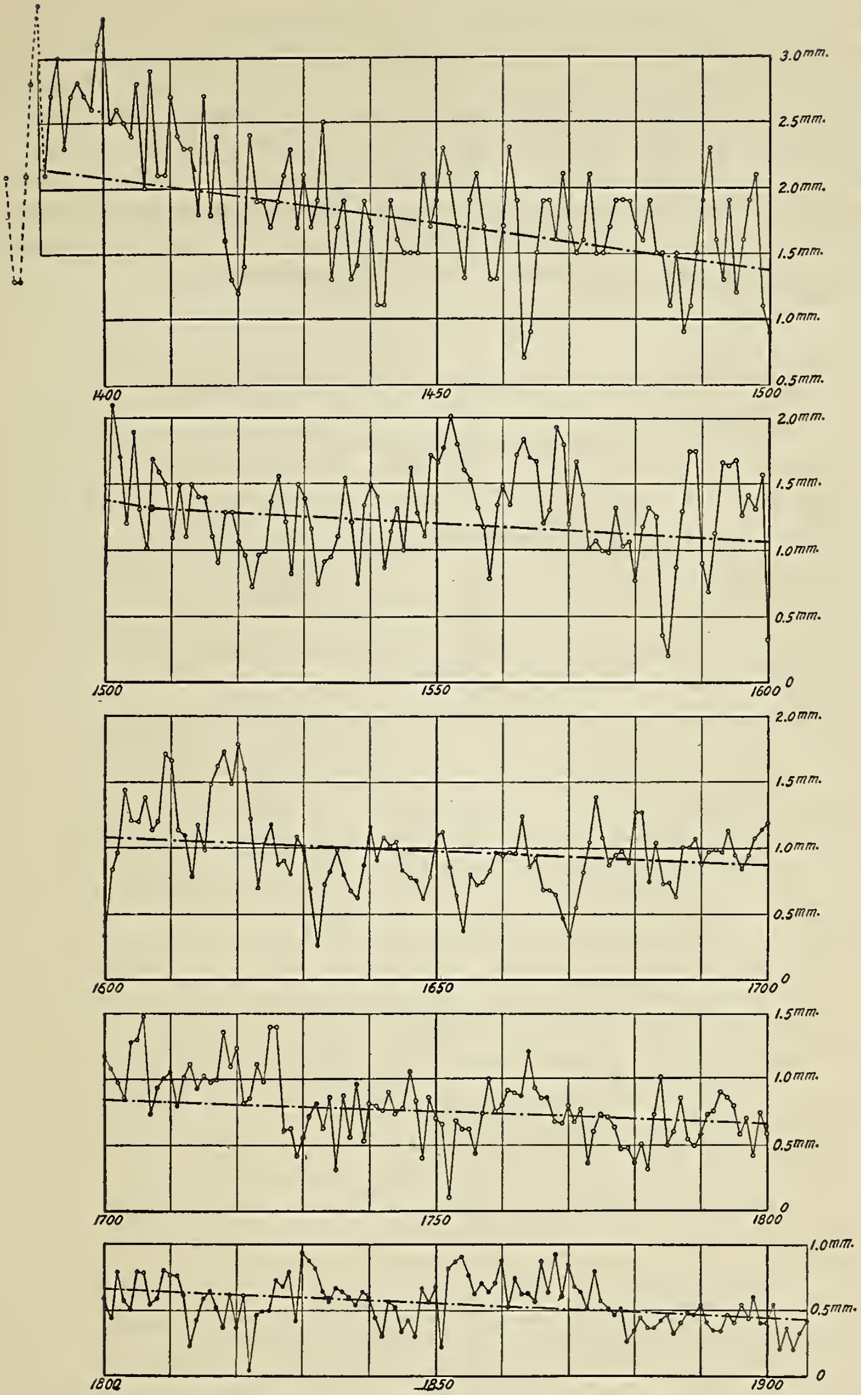


Fig. 3.—Annual growth of trees at Flagstaff from 1385 to 1906, A. D.

only. A comparison between the 5 and these oldest 2 taken by themselves give an agreement not absolutely perfect, yet so close that errors thus introduced will not materially affect the curves. However, the oldest 2 were very slow-growing trees and they required on the average an increase of about 30 per cent in order to make their curve continuous with the whole 5. Thus the tree-record is made to begin at 1385. In the recent years of the record also, between 1891 and 1896, a slight correction was made for omitted rings, the complete omission of a ring being an exaggeration that introduces error.

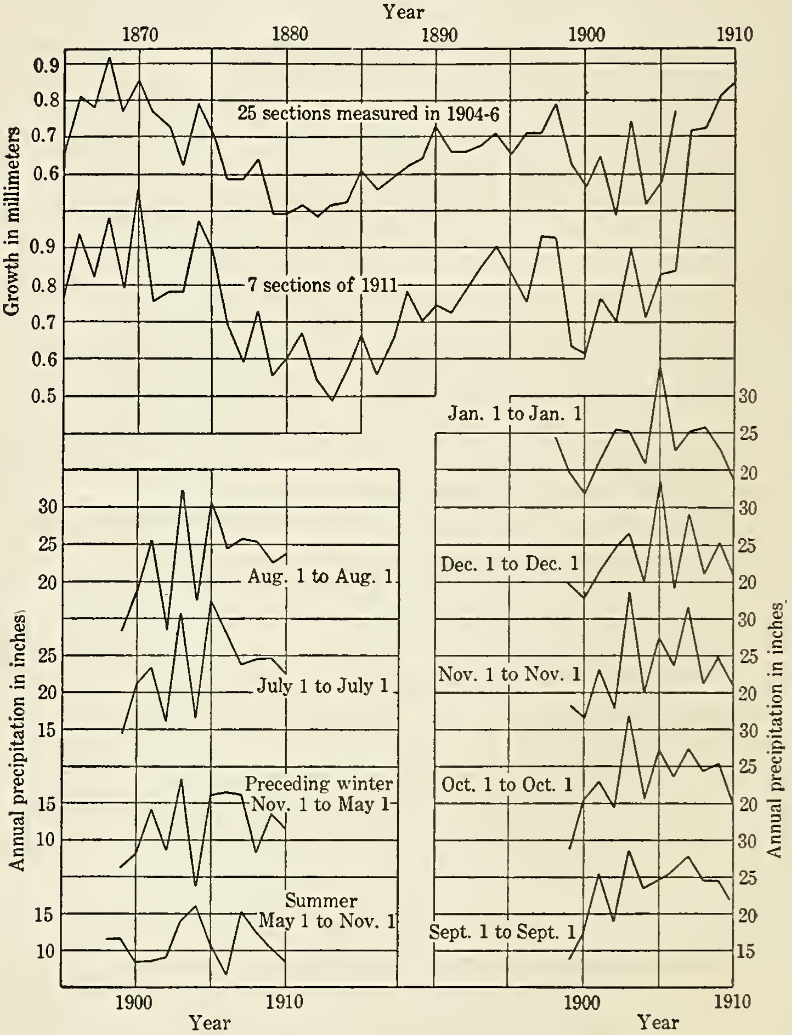


FIG. 4.—Comparison of two Flagstaff groups. Variations in annual rainfall according to month of beginning annual means.

THE SECOND FLAGSTAFF GROUP OF SEVEN SECTIONS.

In 1911 the writer visited Flagstaff again and made a trip into the forest where cutting was going on, in order to procure a few additional samples of the yellow pine which would check the recent part of the tree-record previously obtained and bring it up to date for comparison with rainfall values. The location was about 12 miles southeast of town and from 6 to 12 miles east of the region from which the first Flagstaff group was obtained. Seven cuttings were procured from the edges of stumps, thus bringing away a triangular pyramid of wood, which included the outer 50 to 100 rings.

Figure 4 shows how well the second group checks the first and indicates that even a small group of trees, no more than 7 in number, is sufficient to give results of considerable accuracy. Indeed, we may go further and say that a single tree under favorable conditions may give results of very great value. This is evident in figure 5, where the 7 sections from the last Flagstaff group are plotted separately, the most rapid grower at the top, just below the rainfall curve, and the slowest-growing tree at the bottom. All rise alike because the conditions of rainfall in 1900–10 were more favorable than in the preceding decade, but all (especially the curve of section 4) show a more or less close relation to the rainfall at Flagstaff, even though that town was some 12 miles away. The great sinuosity which a quick-growing tree may show is well illustrated in section 4 in the great differences between successive years. A lack of sinuosity is shown in section 5 at the bottom. This difference supports the conclusion already reached that slow-growing trees are of less value than rapid ones in the determination of climatic cycles. The results of the measures of this group serve as a check on the preceding measures and are shown in the figures just referred to. They are, therefore, not tabulated in this book.

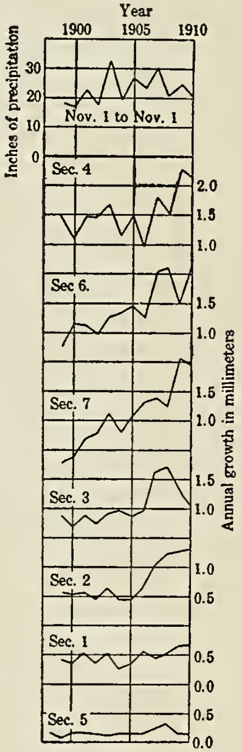


FIG. 5.—Growth of individual trees compared with precipitation at Flagstaff.

THE PRESCOTT GROUP.

Prescott is located in the northerly part of the Bradshaw Mountains, at an elevation of 5,200 feet. The rocky subsoil is largely granite disintegrated at the surface and worn into steep hillsides, deep gorges, and picturesque masses of rounded boulders. The ridges are sharp and rugged, and the general contour is very irregular. There are very few isolated peaks. The mountains are covered with pines from their crests to a little below the level of the city.

This Prescott group was obtained in 1911 for the purpose of testing the conclusions derived from the Flagstaff trees some years earlier.

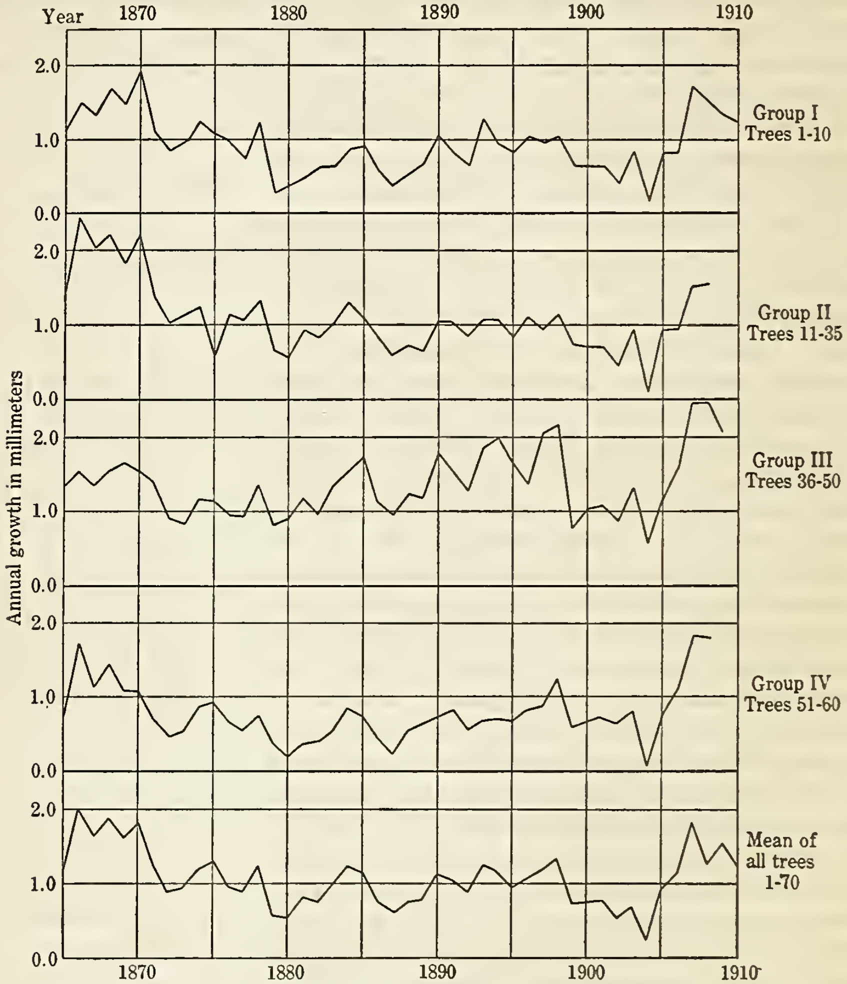


Fig. 6.—Annual growth of trees near Prescott, Arizona.

It consists of 67 trees selected in 5 subgroups depending on their nearness to town. The farthest was 10 miles southeast and the nearest was 1 mile south. It was apparent that the agreement between growth and precipitation increased as the location of the actual rainfall station was approached. The nearest subgroup, containing 10 trees, shows so much greater agreement than the others that it has been used alone in drawing final conclusions. Its site was a small, poorly drained level space near the bottom of the valley.

In this group there was no necessity of duplicating the Flagstaff records, and therefore small V-shaped cuttings were made at the edges of the stumps, only triangular pieces of wood giving the outer half century of ring-growth being brought away. These were the samples on which the value of the cross-identification was discovered, as already described. Identical series of rings were observed in nearly every tree of the group.

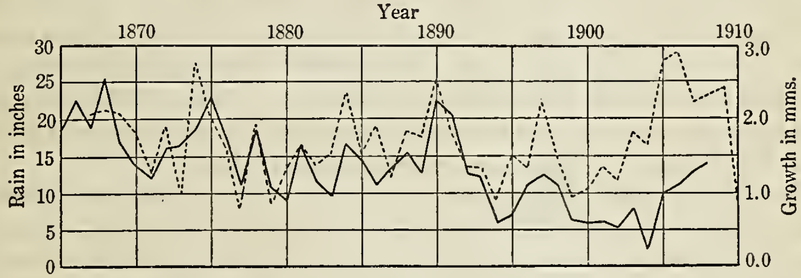


FIG. 7.—Annual rainfall and growth of trees (Group V) at Prescott. Dotted line: rainfall. Solid line: growth.

Out of 67 sections averaging 50 rings each, only 6 gave any identification trouble. In 2 of these, 2 rings were lacking, but when allowance was made for this defect the identification was satisfactory. Another section had 2 extra rings, and another had 2 extra and 3 lacking. The other 2 sections proved especially puzzling and were finally omitted from the means. Of these 6 troublesome sections, the first 5 were very slow growers. Hence it would seem advisable not to use extremely slow-growing trees any more than is necessary. It may be urged that trees do not grow continuously at the slow or fast rate and that we can not tell how much of the change is due to rainfall. On the whole, however, it seems advisable to exclude trees or parts of trees whose identification is extremely difficult. The inner rings if well identified may be extremely useful in carrying back early records, as the slow-growing trees are likely to be among the oldest.

The averages of 4 subgroups and the means of all the Prescott trees will be found plotted in figure 6. The curve of the fifth subgroup is given in figure 7, where it may be compared with the rainfall of Prescott.

SOUTH OF ENGLAND GROUP.

This group of 11 sections was obtained in January 1913 at Fleet, near Aldershot, some 30 miles west-southwest of London. The trees were the common pine, *Pinus silvestris*, and averaged about a foot in diameter. The growth was very rapid and the wood was full of moisture. The trees had formed a border to a little plot of cultivated land with a southwesterly exposure. The average age was 54 years. The rings were all extremely plain, averaging 2 to 4 mm. in size, and cross-identification was everywhere perfect. Of the 50 or 60 rings, about 10 had marked characteristics and were easily recognized in nearly every section. It was noted that a few sections had numerous rings more sharply defined on the summer side of the dense red portion than on the usual winter edge. One of the 11 sections is shown in plate 3, A.

The appendix contains a table of mean tree-growths of the 11 British sections; the years 1859 to 1863 inclusive show means of 6 trees only, as some did not extend back that far; of these, 2 had their centers about 1858, 2 in 1857, and 2 in 1855. The owner of the land informed me that the trees had all been planted at the same time, and therefore this apparent discrepancy may be due to sections cut at different heights above the ground. These means are plotted in figure 8.

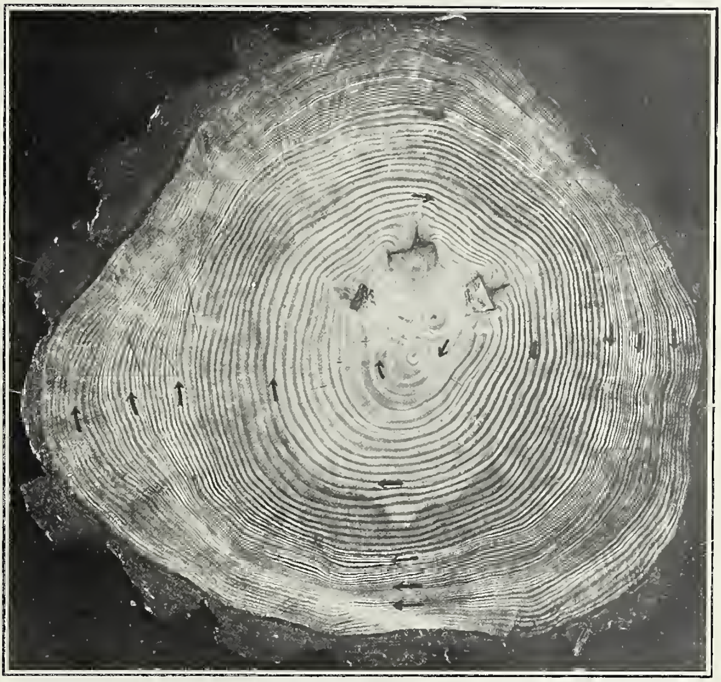
For ready comparison it seemed desirable to standardize this British curve as well as each of the other European curves. Each curve is therefore corrected for changing rate of growth with age and also very slightly smoothed to get rid of the confusing effect of the 2-year "seesaw" described later. In the present group, after careful consideration, the standardizing line follows the tree-growth through a uniform curve in the earlier years and becomes straight in the later years. Percentage departures from this mean standard line give the standardized curve. These percentage departures smoothed by Hann's formula will be found plotted in figure 23, together with similar curves from the other European groups.

OUTER COAST OF NORWAY GROUP.

On the advice of Dr. H. H. Jelstrup of Christiania, I visited the Forest School of Sopteland, a small place located about 18 miles south of Bergen, near latitude 60°. The elevation is but little above sea-level, and irregular intervening hills give slight protection from the North Sea storms. This group of 10 *Pinus silvestris* sections was collected on January 3, 1913, from logs in the yard of the Forest School. The logs had been cut within a week or two in Ös, 12 miles to the south, on an exposed part of the coast and probably close to sea-level. Ös is on the north shore of one of the larger inlets entering on the north side of Hardanger Fjord.

The average diameter was 6 to 8 inches and the average date of the center was about 1840, but one extended back to about 1800 and another to 1700. The average size of rings was about 1.25 mm. The group cross-identified extremely well and on a preliminary inspection seemed to show somewhat rhythmic variations in growth. In these

A



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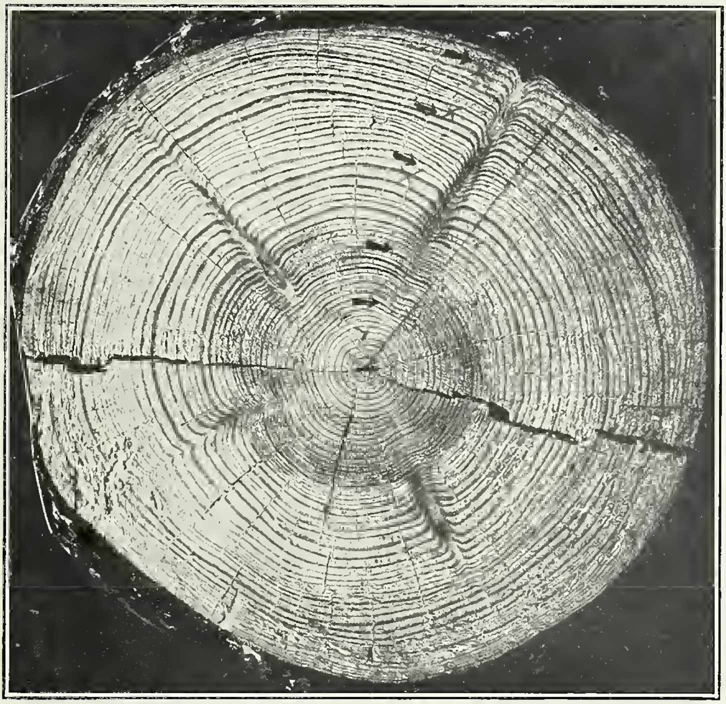


A. Section of Scotch pine from southern England.
B. Section of Scotch pine from coast of Norway.

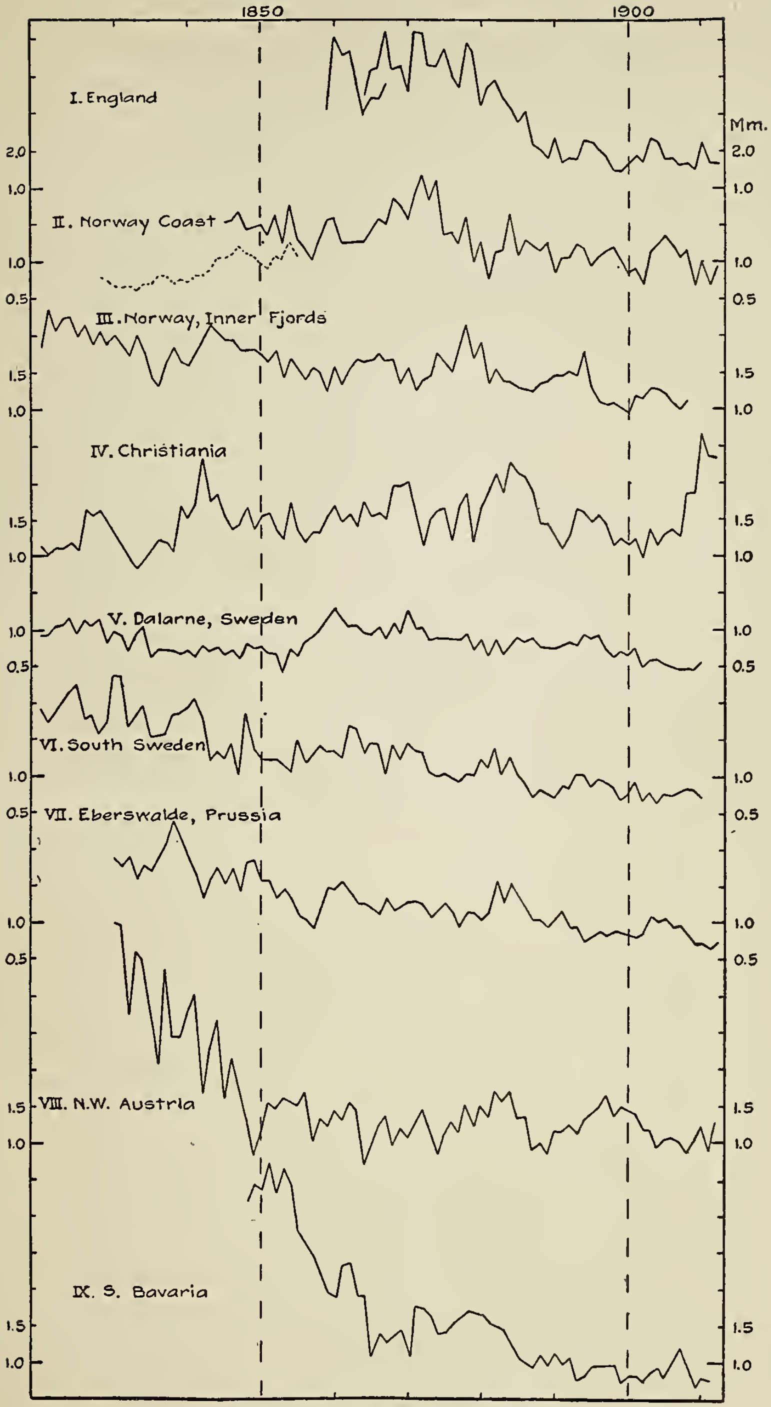


FIG. 8.—The nine European groups.

sections there is more than usual variation in different radii, an excess of growth starting in one direction and then slanting off in some other direction. Here it was found also that maxima were not always the same in different radii. It was suspected that some radii tried to follow a single cycle and others a double cycle. A photograph of one of these sections is shown in plate 4, A.

The appendix presents a table of mean growth of this group from 1845 to 1912. No. 2 had its center in 1865, and between that date and 1845 extrapolated values have been used in forming the means. These extrapolated or artificial values preserve the average shown by the individual tree during its years of growth, but are made to vary from that average in accordance with the variations of the rest of the trees in the group. From 1828 to 1844 the mean of 3 sections only is given. The actual mean has in this latter case been multiplied by 1.25 to bring the average into accord with the group, for the mean of these 3 for the 11 years from 1845 to 1855 inclusive is only 80 per cent of the mean of the group. In this group one center was in 1865, three in 1844, one in 1842, one in 1840, one in 1836, one in 1827, one in 1800, and one in 1693.

These means are plotted in figure 8. The same corrected to a standard mean and smoothed by Hann's formula will be found in figure 23. No real correction for age has been made in this case, for there seems little change in rate of growth that can certainly be identified as such. The whole, therefore, has been simply reduced to scale for comparison with other groups by dividing every year by 1.25, which is very nearly the average growth in millimeters.

INNER COAST OF NORWAY GROUP.

It is a great help to visit the exact locality in which the trees grew, or to get very near it, as in the groups already described, and especially to obtain personal information in a mountainous country like Norway, where meteorological conditions may vary enormously within a few miles. But it was impossible in the present group, whose sections had mostly been collected some years before for use in the forest service and schools. By courtesy of various officials I was permitted to examine and measure these sections in their offices, and whenever it was possible thin sections were cut off for me to add to my collection. In measuring sections of which samples were not retained, for example B 15, B 16, and N 2, there was no opportunity of cross-identifying rings, and hence unusual precautions were observed in numbering the rings. If at any spot they seemed to be very close together with any chance whatever of mistake by omission or doubling, the numbering was carried to as many other radii as were necessary for a check, and worked over very carefully until the best possible result was obtained and all doubt seemed to be overcome. Nevertheless, judging by past experience, unchecked counting leaves a doubt wherever the rings are reduced to 0.1 to 0.2 mm. in thickness.

Another disadvantage of this group is that the trees came from very diverse localities, and hence do not represent homogeneous conditions. Therefore, each section in the group will have special mention. The first number in the group, B 11, was cut from a log of *Pinus silvestris* lying on the woodpile in the yard of the forest school at Sopteland. The tree had been brought in for firewood late in 1912, but was undoubtedly dead at that time, for the outermost ring checked with the Os group unmistakably as 1911. This view was supported by the decayed bark and moldy trunk. This section was 9 by 14 inches in size and had the center (date 1734) some 3 inches from one end, producing one of the most uniform cases of eccentric growth which I have seen.

Nos. B 12, 13, and 14 cross-identify most satisfactorily with the Os group. From one to six individual characters or a most convincing sequence of characters were obvious in every decade. Section 12, a foot across, was cut in 1909, and the last complete ring was unmistakably of 1908 by comparison with the previous group. A section was cut for me at the school in Sopteland. The original was marked "No. 1, 1909, Knagenkjelm, Kaupanger," a location on Sogne Fjord, some 80 miles northeast of Bergen. My section shows the bark and very dense, handsome wood with strongly marked rings. Its center is at 1682. No. B 13, center at 1807, is of about the same size and from the same place, and was marked "No. III, 1909." Its outer ring also identified as 1908. A portion of this section also was cut for me.

No. B 14, center 1779, was marked "No. 1, 1909, Lyster Sanatorium," on Sogne Fjord. As in the other two cases, its outer ring was plainly 1908. A thin section was cut for me. Its size was 12 by 14 inches. B 16 was marked "No. 3, 1909," from the same place. This huge section was 28 inches in diameter and 7 inches thick, and its center was about 1724. There was a series of very small rings from 1787 to 1794 and another from 1806 to 1813. I have no section of it and so no cross-identification could be attempted, but the measures of the recent years agree with No. 14 from the same place.

No. B 15, center at 1633, was also measured at the school and no section retained for comparison with the others. It is the only one from its locality. It was marked "No. 1, 1909, Nestaas, Granvin," on Hardanger Fjord. It was cut in October and the first ring was considered to be of that same year. The rings were very clear back to 1680 and in fact to the center, but between the center and 1680 they were very small.

All the sections so far in this group came from the west side of Norway near latitude 60°. The remaining two came from farther north and were first examined in the office of Dr. Jelstrup. No. N 1 was a small tree some 6 inches in diameter with its center in 1848. It grew in Mo i Ranen in latitude 66° 15′, a 2 days' trip by boat from Trondjem. The rings show a rhythmic character, and a photograph of the thin section presented to me is given in plate 3, B. As in the other similar photographs, the years of sunspot maxima are marked with arrows. It was cut in 1907 and the outer incomplete ring was taken as of that year. The identification with trees from near Bergen is poor, as would be expected.

No. N 2 was an interesting cross-shaped section from beyond the Arctic Circle, latitude 68° 45′. It had been damaged by forest fires at various times to such an extent that the injured parts of the trunk ceased growing while the rest kept on; hence it was of this extraordinary shape. It was cut in the winter of 1905–6, and the outer ring was taken as of 1905. As a rule the rings were very easy to follow until before the year 1600, and even then by carrying the ring to other arms the identification seemed practically certain. The rings reached a suspiciously small size between the center at 1497 and 1512.

The measuring of this 400-year section was done on December 31, 1912. By noting ring after ring with care, tracing all rings a short distance and following the one case of suspected double across into another arm, there seemed to be no errors, certainly none of doubling and none suspected of disappearance. Letters B, BB, indicating maximum growth, were placed at the center of groups of large rings as the measuring progressed, without knowledge of any relation between them. That same day, on looking over the measures, a Brückner period seemed indicated. The maxima were marked as the measuring progressed. See table 3, on page 35.

This series of maxima, 270 years long, from 1561 to 1830, shown in figure 38, permits the application of a 34-year period with an average error of less than 3 years. If that case were alone, I would not include it here, but I believe I shall be able to show it in a number of very old trees in widely separated localities.

From the above description it is evident that we have in this group some very interesting trees, even though they grew far apart. They are probably worth more as individuals than as a group, but until more trees can be added from their various localities the usual method of presenting them here is used. So the group means are tabulated in the appendix, using an extrapolated value of N 1 from its center in 1848 back to 1821. These means will be found plotted in figure 8. They have been corrected for age and reduced to standard size in the usual way by a straight sloping line reading 1.90 mm. in 1820 and 1.15 mm. in 1910. The corrected means smoothed by Hann's formula will be found plotted in figure 24.

TABLE 3.

Date of maxima as marked.	Differences in years.	Suggested maxima on 34-year period.	Residuals.
1830	....	1831	−1
1797	33	1797	0
1754	43	1763	9
1696	29	1729	1
	29	1695	
1657	39	1661	−4
1528	29	1627	1
1561	33	1593	2
	34	1559	
1535	26?	1525	10?

CHRISTIANIA GROUP.

This group of 5 *Pinus silvestris* sections was secured from logs at a little sawmill in the outskirts of Christiania. The logs cut in the neighborhood were in a large pile at the mill, and after the snow was brushed from them suitable ones were selected. Usually in such cases the largest and oldest were taken, but in this group the growth was exceptionally complacent. Accordingly, preference was given to those which showed variability in size of rings.

These sections were measured a month or two later. Cross-identification proved very unsatisfactory. Large variations were found in the 5 specimens. On this account it was felt that there might be several errors in this group which could perhaps have been removed by a larger number of trees for intercomparison. The centers of the 5 were respectively at 1848, 1824, 1797, 1807, and 1790. The average diameter was about 1 foot. On page 114 will be found the mean growth of these sections and the plot of the same will be found in figure 8. There seems no special change in growth with age, and the whole series was merely reduced to percentages by dividing each yearly value by 1.50 mm. These values, smoothed by Hann's formula, will be found plotted in figure 23.

CENTRAL SWEDEN GROUP.

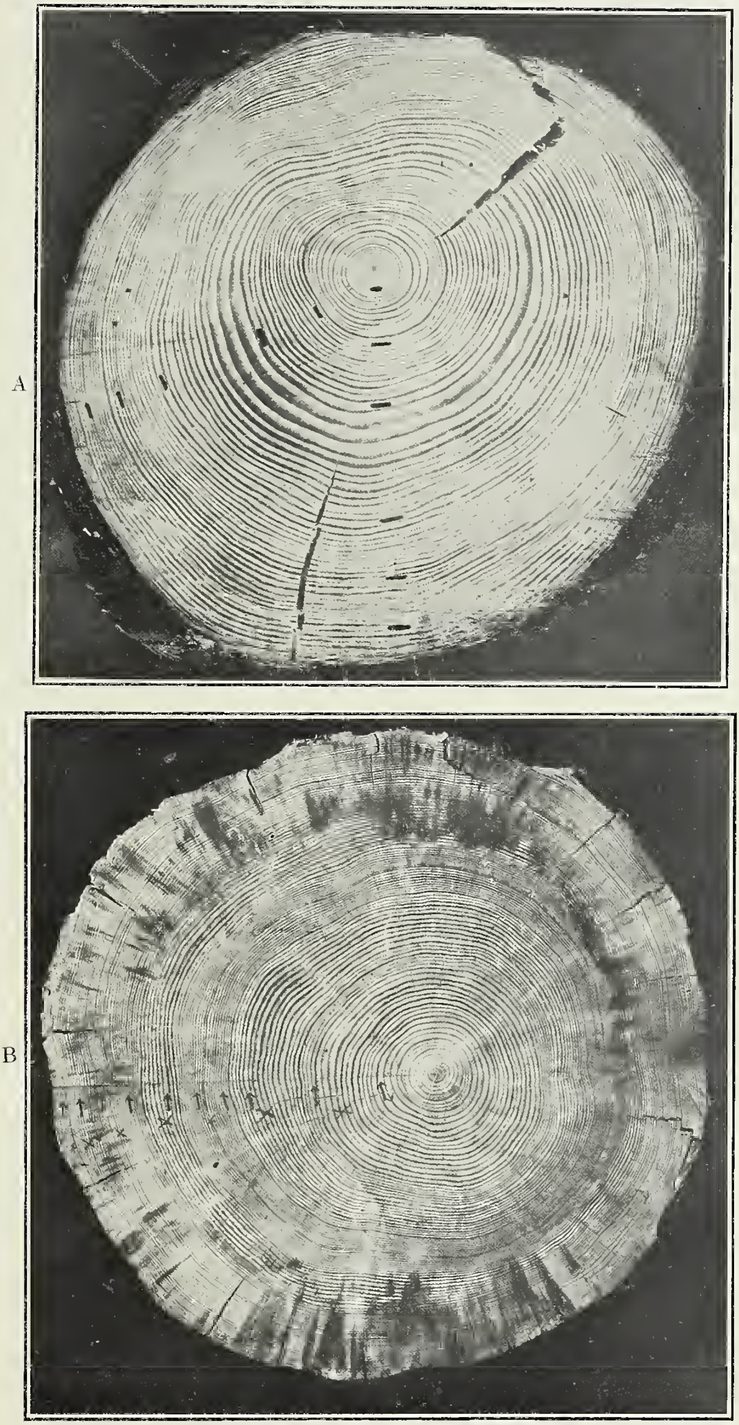
These 12 sections, showing an average diameter of about 11 inches and an average age of 190 years, were obtained from the sawmill near Gefle, on the coast, 60 miles north of Stockholm. The mill, one of the largest in Sweden, was some 4 miles from the town, on the river coming from the interior. The logs came from the vicinity of Dalarne in central Sweden, a large district. The bark is taken off as required by law and the logs are floated down to the mill. I visited the mill on Saturday, December 28, 1912. Twelve sections had been cut, but they were too thick and the whole 12 were cut a second time. These logs had been in the water a year and the last ring would therefore be of 1911 or possibly 1910. Of the 12, I think that all but 2 or 3 show the 1911 ring. Though these sections must have come from a considerable area (unless in the water and mid-afternoon darkness they accidentally secured original neighbors from thousands of logs), they identify among themselves extremely well. Cycles or pulsations were noticed and marked on all the sections of this group before identification. No. S 8 seems the most regular; a photograph of it is reproduced in plate 4, B. The cross-identification for the last 100 years hardly needs review, as it is entirely reliable and practically nowhere are there doubtful rings.

The means of the years 1820 to 1910 are given in the appendix and a plot of the same will be found in figure 8. The tree-growth in this group and others before 1820 will be taken up separately. There seems to be here no real change of growth with age, and the values were changed to standard by dividing by 0.8 mm. These results were then smoothed by Hann's formula and plotted in figure 23.

SOUTH SWEDEN GROUP.

This group of 6 sections was measured at Stockholm on December 27, 1912, in the office of Professor Gunnar Schotte, chief of the Swedish Forest Service. In my lists they are numbered from S 13 upward. They are all *Pinus silvestris* save S 14 and S 17, which are spruce, *Picea excelsa.* No. S 14 is noted particularly because it showed as perfect a sun-spot rhythm as G 8 from Eberswalde, whose photograph is given in plate 8, A. An entirely satisfactory cross-identification was made at the time of measurement.

The individual trees came from different localities and are therefore mentioned separately. No. S 13 was marked "4105–6" and was cut in May 1909. It grew about 100 miles southwest of Stockholm, in latitude 58° 40′. About 1833 it has a doubtful ring which was settled by comparison with other measures. Its center was in 1763. No. S 14, a *Picea excelsa,* marked "4105–14," was cut in July 1910 on the east side of Vetter Lake, less than 100 miles southwest of the preceding. Its center was in 1816. No. S 15, marked "4105–2," was cut in August 1909, about latitude 64° 30′, near Lycksele, Lapland. It showed clear and well-sized rings to its center in 1701. No. S 16, marked "4131–a1," was cut in August 1910, in Elfdals, in latitude 61° 24′. Its center was about 1838, but its inner 10 rings were uncertain and therefore not



A. Section of Scotch pine from Ös, Norway.
B. Section of Scotch pine from Dalarne, Sweden.

used. No. S 17, *Picea excelsa,* marked "4105–5," was cut in May 1909, in the same locality as S 14 and shows a similar rhythm. Its center was in 1777. No. S 18 was a small section marked "4131–a–12." It was cut in October 1910, in latitude 58°, well to the west of the others. Its radius measured only 2 inches. The average diameter of the other sections was about 12 inches.

On page 115 will be found the means of these sections, with two extrapolations, one from 1820 to 1848 and the other from 1820 to 1878. This curve will be found plotted in figure 8. It has been corrected for age and reduced to percentages by dividing by the readings of a straight line extending from 1.90 mm. in 1820 to 0.70 mm. in 1910. This corrected set has been smoothed by Hann's formula and will be found plotted in figure 23.

EBERSWALDE (PRUSSIA) GROUP.

These 13 trees were cut and sections prepared for me by the kindness of Professor A. Schwappach of Eberswalde. They were all *Pinus silvestris* planted about 1820 to 1830, exactly alike in height and size, with tall, straight, clear trunks about 10 inches in diameter and bushy tops. The land is a gently rolling country with a slight northerly slope, leaf-covered ground, a sandy soil with loam on top, and an elevation above the sea of 200 to 300 meters. The height above the city level was 200 feet or so; the locality was south and west of Eberswalde station. The trees cut were scattered along a quarter of a mile and so did not represent any close grouping. Their rings show almost identical records; 2 to 10 in every decade have enough individuality to make them recognizable in every tree.

On the first examination of these sections in November 1912, it was evident that their growth follows with fidelity the sunspot curve since 1830. This may be traced in the curves below and in the accompanying photographs of two of the sections in plate 8. It will be seen at once that there is a rhythmic sway in the growth, groups of large rings alternating with small ones. The arrows placed in the photographs mark the years of maximum sunspots. Taking the group as a whole, the maximum growth comes within 0.6 year of the sunspot maximum. To one maximum alone they fail to respond, namely, 1894; instead of rising, the curve drops in 1892, 1893, and 1894. I have tried to find cause for this, but was informed by Professor Schwappach that there were no fires, pests, or other known causes for it except climatic conditions.[1]

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[1] Schwappach. Zeitschrift Forst- und Jagdwesen, September, 1904. A recent bulletin of the Mellon Institute, by J. F. Clavenger, entitled, "Effect of the soot in smoke on vegetation," suggests at least a possibility. Clavenger shows photographs of tree sections in the neighborhood of iron mills, in which the growth is normal until the smoke from the mills pours over the forest, and then the rings rapidly decrease in size. It would solve the puzzle if it could be shown that smoke from the iron and brass works in the neighboring city came over the forest of Eberswalde more abundantly at about this time. Dr. Schwappach writes that the manufactories and repair shops are 3 km. distant and in his opinion the decrease in growth can not be due to smoke from them.

On page 114 will be found the Eberswalde means from 1830 to 1912. Only one center occurs later than that date of beginning, namely, 1833. The others were mostly between 1821 and 1827. The means of this group are plotted in figure 8 and also shown more in detail in figure 9. These means have been corrected for age and reduced to percentages of a mean line reading 2.57 mm. in 1830 and 0.54 mm. in 1910. These in turn have been smoothed and plotted in figure 23.

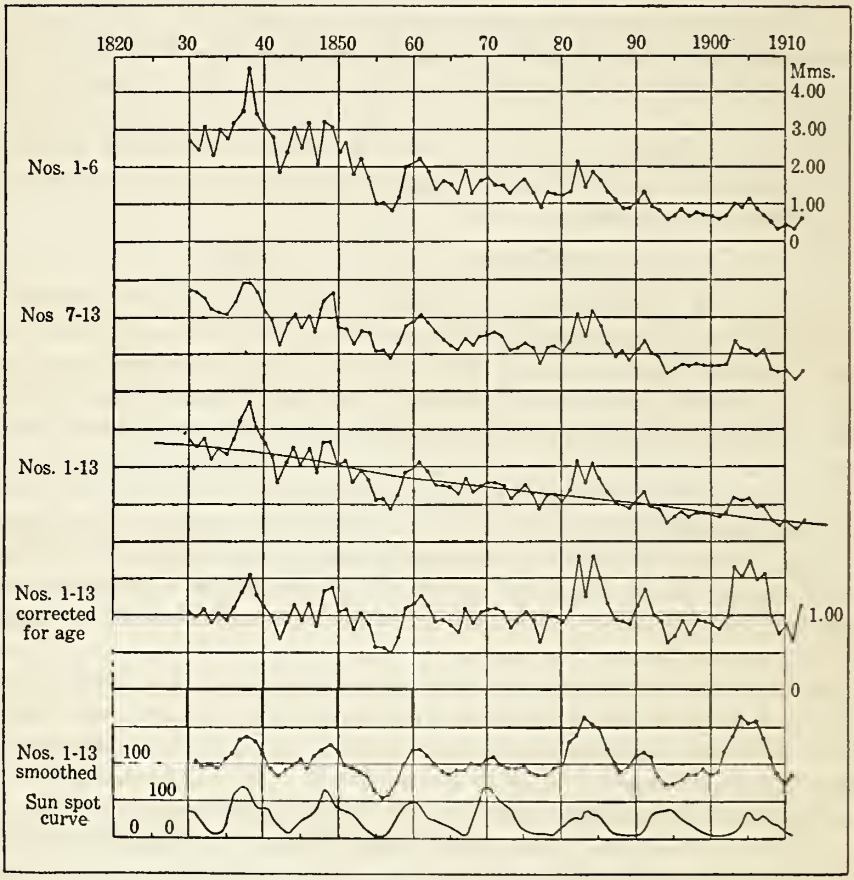

FIG. 9.—Sunspots and growth of trees at Eberswalde, Germany.

In considering the significance of the agreement above noted, one should, in my opinion, keep in mind first the unusually homogeneous environment of these particular trees and the great care they have received, and second, the suggestion they contain of eventually defining distinct meteorological districts in which homogeneous effects are noted. A small pine of 60 rings from the Hartz Mountains was examined in the

Geological Museum at Berlin, in which the same cycle was prominent. It was not measured, as the date of cutting was not known.

PILSEN (AUSTRIA) GROUP.

This group of 7 *Pinus silvestris* sections was measured in the office of Dr. A. Cieslar, in the Hochschule der Bodenkultur at Vienna. I have no samples of them in my collection, but they were carefully cross-identified before measuring. Two sections had the ring for 1849 very doubtful, but its identity was verified by comparison with the others. The average date of the center was 1821 and the average size 11 inches in diameter. They all came from a forest station near Pilsen, in northwestern Austria. I have not seen the locality, but judging by the appearance of the country a little farther south the mountains are not rugged.

The mean measures upon this group from 1830 to 1912 are given on page 114; their plot is in figure 8. The curve is very peculiar, and it is hard to say how it should be corrected for age. It descends sharply from 3.62 mm. in 1830 to 1.25 mm. in 1851, and from that point on it remains 1.25. This bent line has been applied, and the resulting percentages have been smoothed and plotted in figure 24.

SOUTHERN BAVARIA GROUP.

This group of 7 *Pinus silvestris* and 1 *Picea excelsa* sections was cut for me by the kindness of Messrs. Klöpfer and Konigen in Munich from logs in their yards. The trees had been cut in the winter of 1911–12 at Altotlinz, Ober Bayern, some 50 miles south, at a considerable altitude, in the northern valleys of the Alps. The rings in all these were clear and distinct and no doubtful cases were found except a very few near the center of two sections, which were omitted in the means; yet the cross-identification was not fully satisfactory. Sections numbered M 2, M 6, and M 8 in this group showed 1 to 2 entire discordances out of about 10 features in the last 60 years. The others agree fairly well. Possibly this condition results from the rugged and non-homogeneous region where they grew.

On page 116 will be found the means from 1848 to 1911. In these, M 6 and M 7 are extrapolated for about 12 years, and M 8 for 2. These means will be found plotted in figure 8. The curve shows apparently a very rapid decrease of growth with age. The correction line assumed is a line reading about 3.15 mm. in 1850, 2.10 mm. in 1860, then with decreasing slope reaching a nearly level line at 0.90 mm. between 1895 and 1911. The means have been reduced to percentages of this line and smoothed by Hann's formula and plotted in figure 24.

OLD EUROPEAN TREES.

It is of course most desirable to carry the tree-records back as far as possible for verification of any feature observed in recent years and for additional information. But one is met by the rapidly diminishing number of specimens and the liability of obtaining records which are not representative of the regions on account of the increasing effect of individual and accidental variations. It is true that in the very homogeneous region about Flagstaff, Arizona, an average of 5 trees and even of 2 gave a valuable record corroborated by comparisons with larger numbers; but in these European groups the oldest trees are all from the Scandinavian peninsula, and probably the individual trees of which I have samples are representative of widely different localities in a rugged and mountainous country. Even though not homogeneous, the 15 oldest trees have been segregated in 2 groups covering the interval from 1740 to 1835.

Group A represents the inner coast of Norway and includes the following trees: No. B 3, Ös, south of Bergen; No. B 11, Sopteland, south of Bergen; No. B 12, Sogne Fjord; No. B 15, Hardanger Fjord; No. B 16, Sogne Fjord; No. N 2, latitude 68° 45′.

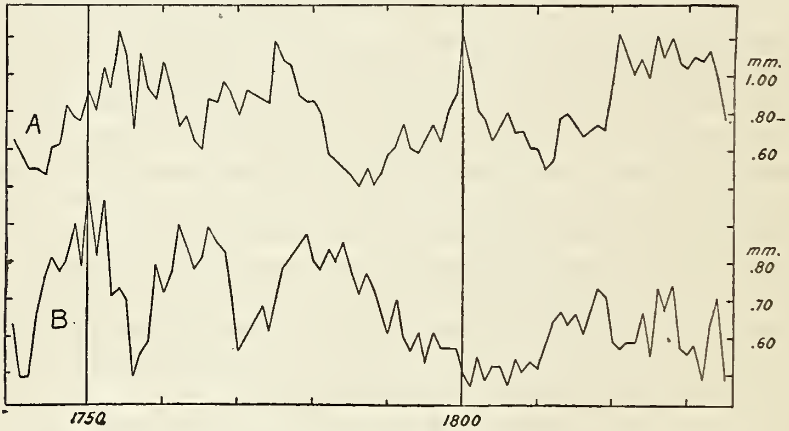

Fig. 10.—Growth of old European trees. *A*, six Norwegian trees, mostly from inner fjords. *B*, eight trees from Dalarne, Sweden.

Group B is made up of 8 trees from Dalarne, central Sweden, and 1 from Lapland, latitude 64° 30′. This group, therefore, represents somewhat more homogeneous conditions, but yet it can not be well summarized in its larger fluctuations. When plotted with Group A, as in figure 10, it shows the latter to have a considerable tendency to reversal, a characteristic already observed in this region. But there are discrepancies in Group B consisting of sudden depressions in growth which suggest injury, as in 1756 and 1769 and 1770. A very regular recovery from these depressions sustains this idea of their cause. The means of the 2 groups are given on page 116.

A few trees are perhaps available for periods antedating 1740. The centers of 5 are as follows: B 12 in 1682, B 15 in 1641, N 2 in 1497, S 4 in 1510, S 9 in 1660. But the first 3 are from separate localities in Norway and the other 2 are from central Sweden, so it seems hardly profitable to include them here in a group on account of the tendency to reversal between those localities. The section N 2, 400 years old, from high latitude on the Norwegian coast, presents a feature of interest as noted in connection with the Norwegian group, namely, a pronounced fluctuation very nearly 34 years in length. The measures on this tree have been plotted, a mean sinuous line drawn through them, and then this mean line transferred to a different scale, smoothed graphically, and photographed to form figure 38 on page 106. The more formal analysis of this interesting tree-record with the periodograph confirms this periodic fluctuation.

WINDSOR (VERMONT) GROUP.

On return from Europe it seemed desirable to learn how American trees react in similarly moist climates. But it was not easy to secure sections. There are very few large pines near the Eastern cities. One "pitch" pine from 50 miles south of Boston, with more than 100 rings, was secured, but there were no others in that immediate vicinity. Five white-pine sections from near Middleboro, Massachusetts, were obtained, but their rings were too few in number, being only 50 to 60. Finally a satisfactory series of hemlock, *Tsuga canadensis*, from Windsor, was collected. Six sections came from the northwest slopes of Mount Ascutney at the lower and very steep end of the Brownsville trail. Five of these I cut from the stumps myself and preserved, and one was measured on the stump itself with full cross-identification. The remaining 5 of the 11 were cut from logs in a lumber-yard in Windsor; they came from across the river on a farm about 3 miles from town. Thus 7 or 8 miles separated these two subgroups. But the whole are here retained in one group, for the cross-identification, though difficult, was perfectly satisfactory. In order to be quite sure on this point, the subgroups were left separate until their curves could be compared. The Ascutney subgroup, with one extrapolation, extends back to 1695, and from that date 2 trees were carried back to 1650. A comparison between the 2 and the whole 6 showed harmonious curves in their overlapping parts. This curve shows an average growth of considerably less than 1 mm. in all its earlier years and up to the year 1808, when its yearly growth doubled. This sudden increase was interpreted to mean that at that time these hemlocks emerged from the shade of surrounding trees. The change was so rapid and great that it seemed likely to be due to the cutting down of the surrounding forest. In this subgroup, also, the years 1770 and 1821 were so extremely small that injury on those dates seemed likely.[1] The other subgroup from east of Windsor extends easily to 1650, with one extrapolation of 20 years and another of 3. It shows no effects in 1770 or 1821, but does show a temporary slight rise in 1807, and then a gradual increase to well over 2 mm. by 1870 or 1880, as would be expected when light-loving trees gradually push their way out into preeminence above their neighbors. A comparison between these two curves in their minor details confirms the view that all 11 may be included in one group.

The means of the Windsor hemlock sections from 1651 to 1912 are given on page 116. In 1651 the figures give an average derived from only 6 sections. This increases to 9 sections in 1694, and from 1695 the whole 11 sections are used. These numbers have been smoothed and plotted, and their resulting curves will be found in figure 27, together with the sunspot curve.

OREGON GROUP.

Following the New England group, a set of Douglas firs was obtained from a logging area about 25 miles northwest of Portland, Oregon. Several points of interest appear in connection with this group. In the first place, the samples were not radial specimens of the wood itself as heretofore, but were pieces of blotting-paper of suitable size which had been rubbed into the tops of the weathered tree stumps. These were made in 1912 by Mr. Robert H. Weinknecht, who writes as follows:

> "The prevailing age on the tract is about 210 years on the stump. The trees selected were average with neither suppressed nor abnormally large growth. An average typical radius was selected on each stump. Twenty-three impressions from this one locality were obtained and sent. Twenty-one came from stumps cut in the summer of 1908, one from a stump cut in 1909, and one from a stump cut in 1912. The method of taking the impressions was one devised by Mr. Higgs and described by him in the *Forest Quarterly* for March, 1912. It was found that fresh stumps gave very poor results and especially poor for the last 50 years. This was attributed to pitch forming near the outer parts of the stump and to the fact that the weathering of the stump had not been sufficient to bring the rings out in relief. Some of the impressions were gone over with a pencil to bring out the rings where they were faint or broken. This was done carefully and checked by the number of rings counted on the stump."

During the course of identification and measurement, it was observed that only a small proportion of the ring impressions show distinctly the ending of each year's growth, which is usually the best measuring-point. In good reproductions the measures are satisfactory, different observers agreeing within 0.1 to 0.2 mm. In others, however, there is much chance for judgment in selecting the measuring-point, and observers differ 0.3 to 0.5 mm. Nevertheless it is easy to judge of the relative sizes of rings and the only injurious effect is to reduce variations.

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[1] A letter was published in the local newspaper, asking if anyone had any information regarding forest fires in 1770 or 1821 or of lumbering in that locality in 1807 or 1808, but no reply has been received.

The cross-identification was very satisfactory, with practically no doubtful cases and only a few which required careful study. It is not likely that there is a single error in identity throughout the 17 sections in this group. Two other trees, one cut in 1909 and the other of unknown date, but probably cut in 1902, were not included. They showed special characteristics, such as an evident injury in 1861–62, affecting the 1862 ring and several others following it. They show also small growth in 1886, and even in 1887 and 1888 following the minimum growth of 1884 and 1885 prominent in the large group. The tree (cut probably in 1902) shows a minute growth in the years 1779 to 1783 inclusive, evidently the result of injury. These two sections are full of character and may prove valuable.

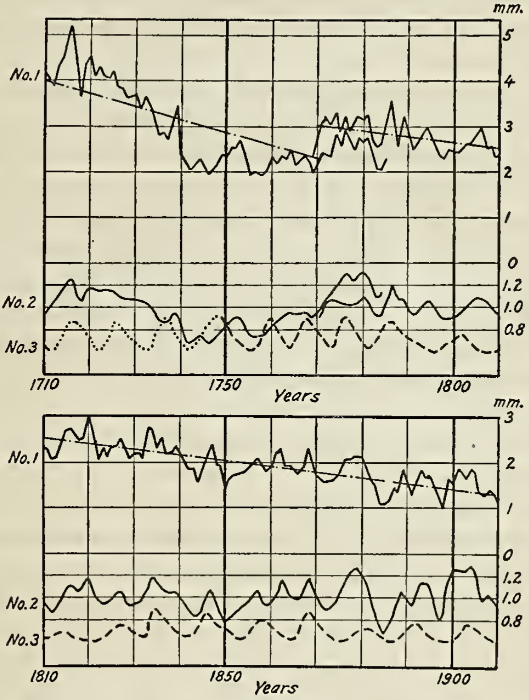

Fig. 11.—Oregon group. Curve No. 1, actual tree-growth; No. 2, tree-growth departures, smoothed; No. 3, sunspot numbers displaced 2 years to left.

Five other rubbings similar to the group of 17 were discarded because defective in some parts. The attempt to trace the lost lines with a pencil-mark gave no help. One of the 17 was defective since

1835, and only the earlier part, ending in 1834, was used. Extrapolated values for the missing part were derived in the usual way. A few short, apparently doubtful, regions of rings required careful study and it was found that well-adjusted illumination of the rubbings was very necessary to their correct reading. When the ring impressions were deep in the paper, the end of the rubbing showing the tree center was held toward the source of light in order that the elevation corresponding to the beginning of the spring growth might be brightly illuminated. When the impressions were shallow and faint, it was noted that the rings became very distinct if the rubbing was held between the eyes and the light, thus giving a very faint and perfectly even illumination. If this did not bring out the individual rings, the rubbing was not used.

The location in which these trees grew was visited in 1918 and general contours were noted. The hills are low and comparatively flat-topped, with disintegrated rocks showing in railroad cuttings. The sides of the hills are steep, and the valley bottom is narrow and usually has a wash near its center. In general the drainage is toward the east, but there is no high and sharp ridge between this region and the ocean on the west. The situation is far enough north to have a good snowfall in winter. It is about 800 feet above sea-level.

The tabular matter giving the results of the measures on the 17 Douglas firs of Oregon will be found on page 117. The plotted values appear in figure 11.

THE SEQUOIA GROUP.

In 1911, after examining the writer's results obtained on the yellow pines, Huntington made an extensive series of measurements on the big tree, *Sequoia gigantea*. He did this work on the stumps themselves by direct counting from the outside. This introduced errors of beginning due to removal or injury of outer rings, and errors of omission which of course could not be checked. In order to correct for large errors of omission, he worked out an approximate correction on the grounds of probability which depended upon a comparison between two or more radii of the tree, and in that way many errors were compensated. In the vast majority of cases, his measures were not of individual rings but of successive groups of ten. I have collected seven of his trees, and after complete cross-identification verify his centers as shown in table 4.

But Huntington's method of working directly on the stump enabled him to get data from a very large number of trees, some 450, in a way that served his purpose very admirably. He was searching for general effects, and accuracy to a year or two was less essential. He wished to approximate absolute values of rainfall in past climates, in contrast with which my chief aim is to get relative and periodic values. These two different purposes supplement each other in a highly valuable manner. Therefore, for him, the determination of the general curve, with an allowance for larger growth near the center, was most important. For that purpose he used both young and old trees. Necessarily he visited places where the trees had been cut. The two chief regions of his measurement were in the King's River Canyon district close to the General Grant National Park, and in an old lumber region near Springville, which is south of the Sequoia National Park.

Following Huntington's route, I visited the former region in August 1915. The town of Hume, the mill-site of the Sanger Lumber Company, is reached from Sanger by daily auto stage and formed, therefore, an excellent base of operations. Hume is at an elevation of about 5,500 feet, on the shore of a large artificial pond, into which the logs are dumped as they are brought down from the camps. A narrow-gage logging road extends in an easterly direction from Hume, high up on the southern side of King's River Canyon. It winds in and out of the various small canyons or basins that empty into the large ravine. The elevation of the log road increases gradually from Hume until it reaches 7,000 feet at Camp 6 and Camp 7, which are about 7 and 9 miles distant respectively.

Table 4.

Sequoia No.	Huntington's No.	Huntington's first year of tree.	Identified first ring.	Distance from center in inches.	Probable date of center.
12	92	17 A. D.	Not ident.	8(?)	....
13	91	585 A. D.	588 A. D.	0	....
14	96	387 A. D.	389 A. D.	0	....
15	59	121 B. C.	159 B. C.	0	....
21	74	1318 B. C.	1304 B. C.	1	1316 B. C.
22	195	1141 B. C.	1086 B. C.	7	1160 B. C.
23	116	1191 B. C.	1121 B. C.	10	1200 B. C.

Camp 6 and Camp 7 are the names of the two recent logging stations. Camp 6 was occupied in 1915 and was located on the eastern side of Redwood Basin. The camp sites are usually chosen in such localities, for in each basin there is an enormous collection of accessible timber. In general the tops of the mountains are very rugged and the slopes exceedingly steep. The upper ridges are apt to be very sharp, but in the higher altitudes there is a tendency for the weathering of the mountain to produce this basin type of contour. From the accumulation of soil and the enormous snowfall in winter these become exceedingly swampy. Below the basin the water is carried by sharp, narrow canyons down very steep grades to the river far below. These groves of sequoias are between 6,000 and 7,000 feet above the sea. The climate at this elevation presents a contrast between an intensely cold winter season with 10 to 15 feet of snow and delightfully mild summers. The latter have occasional thunder-storms whose waters quickly run down the mountain slope. Thus conservation plays an important part in the growth of these trees by rendering the winter precipitation more important than the summer and by permitting the moisture to remain long in the swampy places.

Three groups were obtained from this general region in 1915. The first of these came from the uplands above Camp 6 close to the west line of section 17, township 13 south, range 29 east. This region may be found on the Tehipite Quadrangle of the United States Geological Survey. The group includes Nos. 1 to 5. No. 1 was a splendid tree, about 19 feet in its greatest diameter, growing at the uppermost limit of the logging area. Its growth was rapid, and yet it was an extremely sensitive tree, showing beautiful variations from year to year. No. 2 was obtained a little lower down and is mentioned here because it has been used as the standard of the whole sequoia group, having probably a more perfect record than any other tree measured. Its center was about 300 B. C. No. 5 was a small tree which was cut just at the time I came within hearing distance. I thought that two blasts of dynamite were set off and found afterwards that only one charge of dynamite had been used to break through the last support of the mighty tree; the other report was the tree itself crashing to the ground. Yet this was a small tree, only some 12 feet in diameter, and its age was about 700 years. It proved of particular value to the whole sequoia group, because it was the only tree on which was obtained the ring of the current year, thus permitting a very important correction to be made in the dating of rings. This had an important bearing on the relationship of rings to rainfall.

The second group included Nos. 6 to 11, and was made about a mile to the north and 700 feet lower altitude in the swampy basin whose outlet was similarly toward the northeast. No. 6 grew at the edge of the little brook running through the basin and its rings proved later very uncertain in identity, because its habit was complacent, *i. e.*, the rings were nearly all alike in size.[1] No. 7 was an improvement on it, and No. 8, which was still farther from the creek, was perhaps the best of this group of 6. It gave a very fine cross-identification with the first group. No. 11 was also very close to the creek near the outlet of the basin and, as with No. 6, it was impossible to be sure of the identification, owing to its complacent character.

The third group consisted of 4 trees from Indian Basin, about 10 miles northwest of the Redwood Basin and 3 miles north of Hume. This basin is a broad, flat, fertile area with an outlet toward the northeast. Four trees were obtained there which Huntington had already counted. Nos. 12 and 13 came from the flat middle area of the basin. No. 12 was not included in the final averaging because its rings

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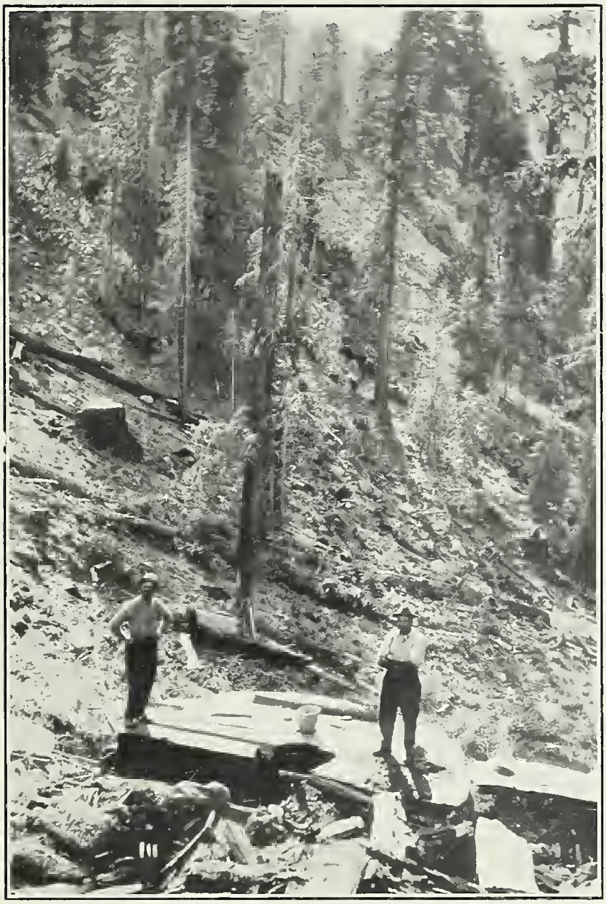
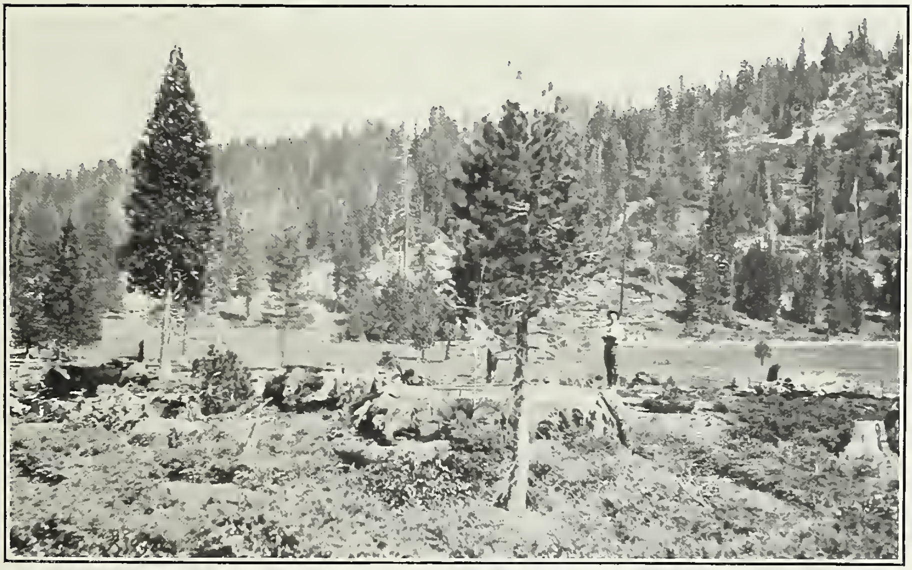
[1] Since the trip of 1919 the identification of No. 6 has been fully established.

A



B



A. Upland contours, above Camp 6 in Sequoia Grove: D–19.
B. Basin contours, Indian Basin, looking S. E.: D–12 and D–13 in center.

could not be identified at all, chiefly owing to large numbers of compressed rings in the last 500 years or more, and to several heavy fire-scars and its generally complacent character. In 1919 a short radial sample was cut from another part of the stump and a complete and satisfactory identification obtained. It shows very fine rhythmic growth in places. No. 13 was not included in the final averages, because its rings were very complacent and perfect identification was not obtained. Nos. 14 and 15 were obtained from the northern side of the valley and their identification was entirely satisfactory. The agreement which they give with Huntington's "first year of tree" has already been quoted.

The three groups whose collection has been described above showed on examination certain interesting relationships to the location in which they were found. The first group was obtained high up on a hillside, where the slope of the ground was 15° to 25°. It was not very far from the top of a sharp ridge and there was no opportunity for moisture to collect and remain for long periods on the soil. Therefore one would expect these trees to show variation related to the amount of snowfall each winter, if any did. The growth of some of these trees was large but full of constant variation, and they were therefore of the type which I have called "sensitive." They do in fact show best of any the relationship to precipitation which will be described in a later chapter. The second group came from a characteristic feature of the country, namely, a basin with thoroughly water-soaked soil.

The luxuriance of vegetation in these basins before lumbering was wonderful. The sequoias grew often within a few feet of each other, and even between them were pines, firs, and cedars. Lumbermen often point out the bottom of a basin and say that such a place ran over 1,000,000 board feet to the acre. To-day nearly all the trees are gone and débris and rubbish are scattered about everywhere. The constant supply of water in the basin made the trees less dependent upon the annual precipitation and they show, in fact, large rings with very slight variation from year to year. They are typical examples of the "complacent" habit. Complacent trees contribute much less to a knowledge of climatic variations, and some of them have to be discarded because of uncertainty in the dating of their rings.

The third group, Nos. 12 to 15, came from Indian Basin, where logging had been done about 1903. Its outlet, like the others, was toward the northeast. It had, however, a much larger flat area, now covered by extensive fields of hay and by forage. The characteristics of the trees found here were the same as in the groups already described.

No. 1 (with a 7-foot radius) was first counted and marked with provisional dates. The rings were coarse and the numbering seemed promising, but proved later to have 6 to 8 errors in the last 700 years. No. 5, which was the tree cut down during my visit, was then dated provisionally. It was 700 years old, with coarse, sensitive rings, and was the only one of the group showing the ring for 1915. In comparing these two for larger variations no accordance was recognized and in details cross-identification failed also, due (as afterwards found) to accumulated errors in No. 1.

No. 2 was then counted and compared with No. 5 with apparent certainty and satisfaction. The former was nearly 6 feet in radius, with small rings, 2,200 years old, and with all but 3 years represented. The last 700 years were thus compared minutely with No. 5 and the earlier parts with No. 1, and one ring (later identified as 699 A. D.) was found to have been overlooked. The earlier parts were later all checked against No. 3 and no suspicion of error was discovered. This number was, therefore, taken as the best type of specimen of this group. Large fluctuations of size rarely occur in it.

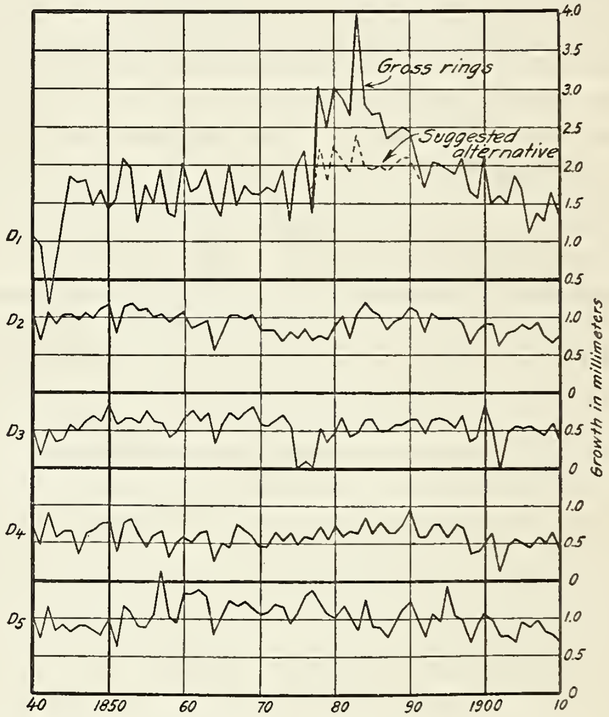


FIG. 12.—Cross-identification in first five sequoias and gross rings in No. 1.

No. 3 was next counted by comparison with No. 2. No. 3 has few large fluctuations and large portions of it match No. 2 with the greatest accuracy. Nevertheless, as a standard with which to compare others, it would be misleading, for it frequently omitted rings; in one place 7 rings and in another 6 rings are entirely missing, and half a dozen more in singles and in pairs. Yet cross-identification with No. 2 was easy and perfectly convincing as to the location of the missing rings.

No. 4 proved to have fairly large rings with 3 to 4 single ones missing and some hard to find, but the identification was easy and entirely satisfactory. No. 1, which was by this time recognized as the most difficult of the group, was reexamined in detail by comparison with No. 5, which proved difficult, with No. 2, which was somewhat better, but especially with No. 4, which proved to have the closest similarity, and all apparent errors were removed. It was very apt to drop out completely rings which were a little below the average. No. 5 seemed to have no tendency to subdue or drop rings. This, with its disclosures of the ring for 1915, showed the necessity of including younger trees in any new group to avoid mistakes in the outer slow-growing parts of the older trees. A comparison of the last 70 years' growth of sections 1 to 5 is given in figure 12. An illustration of "gross" rings is seen in the upper curve.

When the second subgroup was compared with the first, two complete omissions from No. 2 and the others of that first subgroup were discovered. This necessitated the complete renumbering of the first five sections.

The sections were measured at this stage of the dating process. The final renumbering was made after the 1919 trip, the purpose of which was settling the identity of a doubtful ring occasionally found between 1580 and 1581. The existence of this ring was established and the necessary corrections on the sections and in the tabular matter in this book have been made. All subsequent comparisons have verified this identification.

THE SEQUOIA JOURNEY OF 1918.

The visit to the Big Trees in 1918 was for the purpose of procuring material so that the tree-record from the 2,200 years already secured could be extended to 3,000 years. It was expected to do this without great difficulty, for Huntington had enumerated 3 trees over 3,000 years of age, and he had placed numbers on the tops of stumps so that these could be readily identified. Nevertheless, in consequence of the occasional absence of a number on the top of a large stump which had been counted by him, a little more care proved to be necessary than was anticipated.

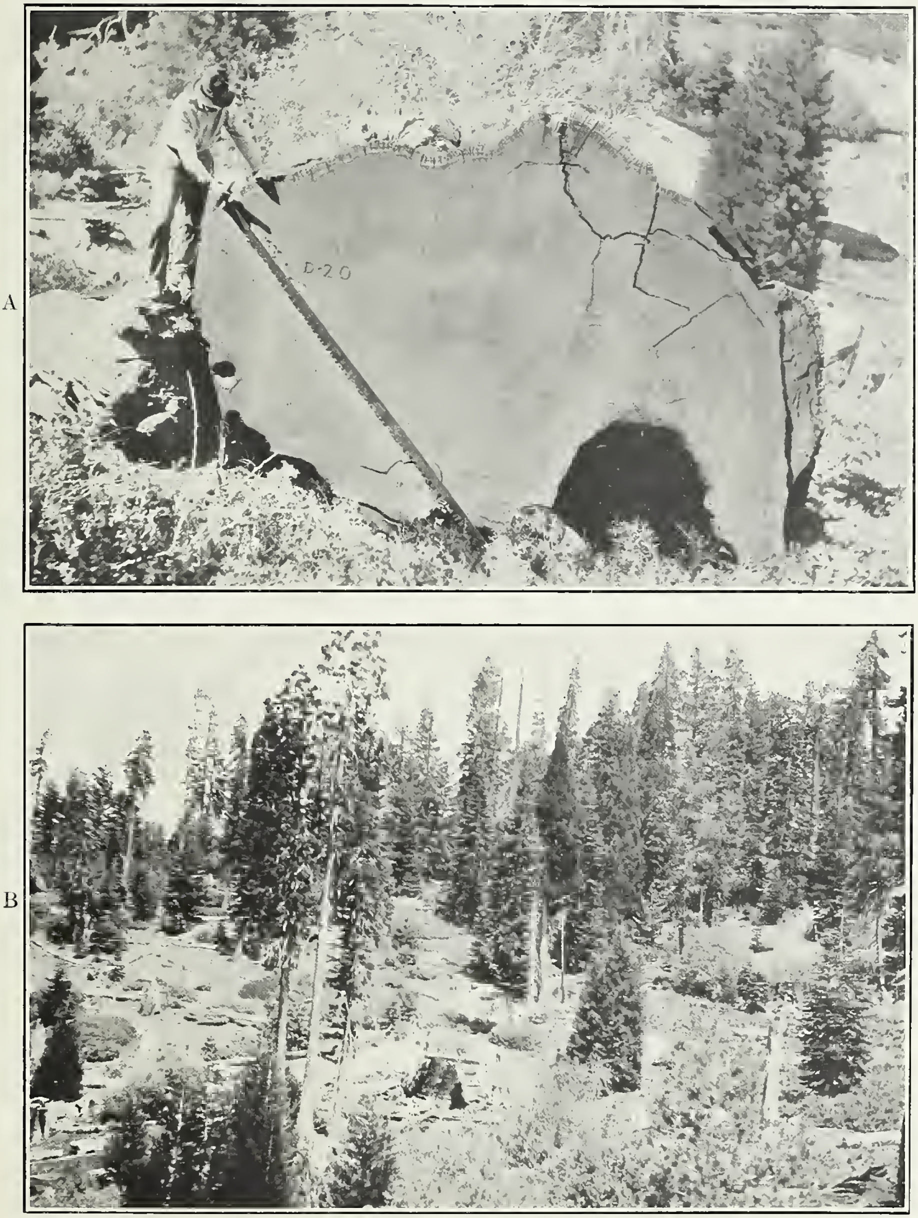
After procuring an outfit in San Francisco, I selected Hume as a base and immediately went out on the log road to Camp 6, the old location of the groups obtained in 1915. All the stumps from which samples had been taken (including Nos. 1 to 15) were visited and each was marked with its respective number preceded by the letter D. This marking was done by a chisel, and the figures were usually about 4 inches in height. Placing the capital D before each number made it certain that no number would be accidentally read upside-down. Naturally the stumps from which samples have been taken show the large cut from center to outside, and there is no doubt about their belonging to the group. But if other samples are taken in future years, this numbering will prevent confusion. All the 23 stumps are thus identified by a number in this series.

I had hoped on this trip to find other trees as old as Huntington's three, and therefore searched carefully for the largest stumps. All those over 20 feet in diameter and a number of less size were estimated for age. This was done by measuring the average width of rings here and there along a radius and multiplying by the length of the radius. About 50 were thus tested. In many cases the result has proved to be within 50 years and sometimes much closer, but these estimations were not very reliable, there being several large mistakes in them. In attempting to pick out the oldest stumps among several thousand without spending much time or getting very far from camp, it is impossible to make these estimates with very great care. It was felt that much help would have been obtained from a small range-finder and telescope, the former to give the distance of the stump and the latter its diameter. In the course of a few days this would have saved many miles of tramping and the oldest trees would have been found more readily.

On the steep upland slopes above Camp 6, two trees were estimated at about 2,500 years in age. These were afterwards numbered D 18 and D 19. D 18 was an immense tree which was cut down in 1914 at the time a motion-picture company was operating in the sequoia forest. It is referred to by the lumbermen as the "Moving Picture Tree." It had to be blasted from the stump before it fell, and the stump was so completely shattered that no sample could be cut from it. In falling, the trunk of the tree split in halves through a large part of its length, and most of it remains where it fell. About 40 feet of logs were cut away between the ruins of the stump and the rest of the tree. Accordingly my sample was cut from the lower end of the broken top and at a point which had been about 50 feet above the ground.

Close by the location of No. 18, and on the steep upper hillside just below the track which extends on to Camp 7, is No. 19. A log from it rests uphill with its upper end at the railroad embankment. The section was taken from the stump nearly 60 feet below (see plate 5). Camp 7 was visited and used as a base for two days. It is 2 miles beyond Camp 6 on the ridge at the farther side of Windy Gulch. There are some very fine stumps close to the road that goes down from the camp into the basin, which were estimated to be 2,300 or 2,400 years old.

No. 16 was found high up in the gulch that extends toward the top of the mountain just south of the camp. The gulch faces toward the east and at the location of the tree has a slope of 15°. No. 17 comes from the basin some hundreds of feet below the camp. It was a windfall and the lumberman thought it might have been lying there a great many years. As it was a very large tree and of slow growth, it was



A. Cutting radial sample from end of log, Converse Hoist: D–20, age 2800 years.
B. Site of oldest tree, Converse Hoist: D–21, age 3200 years.

hoped that its center would prove of very great age. But the results were disappointing, for it turned out that it had fallen only a few years before the logging began and that its age was only 2,200 years. It had so many compressed rings in its outer parts that the last 800 years were not considered worth measuring.

On leaving the vicinity of Hume several days were spent at the General Grant National Park. It formed an ideal center for a considerable region. Horseback trips were made to the area which Huntington calls the "World's Fair District," "Converse Hoist," and by other names. No. 20 was a fallen tree with a northerly exposure, on the west side of the upper basin, not far from the old hoist at the top of the ridge. It was on the west side of the abandoned railroad. It was found that the tree fell only 6 years before the logging was done. A log had been taken out and the sample was cut from the top of the fallen stump. No. 21 is the most interesting of all, because it gives the oldest record by nearly 200 years. It is on the east side of the railroad and brook in the lower part of the upper basin, and some 30 feet above the level of the brook. It is not at all impossible that during its long life the topographic character of the ground about it has altered materially. It is somewhat complacent in its later growth, but this does not persist throughout its record. The top of the stump had carbonized, become extremely brittle and very hard to cut. Though bits of wood broke off and clogged the saw, every piece was marked and preserved. The radial sample has been glued together in the laboratory and is now 9 feet long. The original center of the stump was badly cracked through contraction in drying, but there were lacking only about 2 inches at the center. The central portion, perhaps a foot in diameter, was not firm enough to be cut out with the saw. It was therefore removed very carefully and is now mounted in a special box in the laboratory. The oldest complete ring in good condition was identified as 1305 B. C. Possibly two more rings may be added. A hundred yards to the south and slightly higher up the hillside is the "World's Fair Stump." This was cut in 1892 at a height of more than 20 feet above the ground, and to-day the stump is very difficult to climb, as the scaffold built around it has broken away.

A trip was made from the General Grant National Park to the upper part of the Comstock millsite, known also as Wigger's. The stage road goes near it and the point is known as "Big Stump." The stump, easily seen from the road, is some 25 feet in diameter with a raised square in the center. The location is in a side basin close to a small brook. An examination of the rings showed that the tree had grown with the greatest rapidity, as the rings were of enormous size. It was estimated to be 1,500 years old. No sample was taken of it.

A trip was also made from the park to visit the General Grant Tree and if possible estimate its age. There is an extensive burnt area on the upper side of the tree in which the rings may be observed. These rings are large, and various estimations of the age of the tree obtained in two different visits gave an average of 2,500 years. Near the General Grant Tree is the stump of what was known as the Centennial Tree. It was said that a section of this tree was exhibited in 1876. Since then the stump has been badly burned and is in poor condition for cutting a sample. Some estimate of the rings showed their size to be large, and the age of the tree, therefore, was not very great, perhaps 1,800 years. This confirms the estimate of the General Grant Tree near by.

TABLE 5.—*Sequoia list.*

Sequoia No.	Huntington's No.	Huntington's first year of tree.	Identified central complete ring.	First complete ring not central.	Estimated loss in center.	Estimated years lost.	Probable center of tree.	Probable age of tree in 1915.	Length of record in 1915.	Location.
					cm.			*yrs.*	*yrs.*	
D1			592 A. D.					1323	1323	Camp 6, Uplands.
2				274 B. C.	4.5	15	289 B. C.	2204	2189	Do.
3			310 B. C					2225	2225	Do.
4			425 A. D.					1490	1490	Do.
5			1202 A. D.					713	713	Do.
6[1]			1125 A. D.[2]					790[2]	790[2]	Camp 6, Basin.
7				594 A. D.	13.5	75	519 A. D.	1396	1321	Do.
8			294 B. C.					2209	2209	Do.
9			311 A. D.					1604	1604	Do.
10			362 A. D.					1553	1553	Do.
11[1]				697 A. D.	7.5	46	651 A. D.	1264	1218	Do.
12[1]	92	17 A. D.		135 A. D.	14	65	70 A. D.	1845	1780	Indian Basin.
13[1]	91	585 A. D.	588 A. D.[2]					1327[2]	1327[2]	Do.
14	96	387 A. D.	388 A. D.					1527	1527	Do.
15	59	121 A. D.	160 B. C.					2075	2075	Do.
16			506 B. C.					2421	2421	Camp 7, Uplands.
17			308 B. C.					2223	1438[3]	Camp 7, Basin.
18			294 B. C.					2209	2209	Camp 6, Uplands.
19				242 B. C.	8	35	277 B. C.	2192	2157	Do.
20			902 B. C.					2817	2817	Converse Hoist.
21	74	1318 B. C.		1305 B. C.	2.3	12	1317 B. C.	3232	3220	Do.
22	195	1141 B. C.		1087 B. C.	12.0	75	1162 B. C.	3077	3002	Enterprise.
23	116	1191 B. C.		1122 B. C.	14	80	1202 B. C.	3117	3037	Do.

[1] Omitted from the means on account of some deficiency in identification.

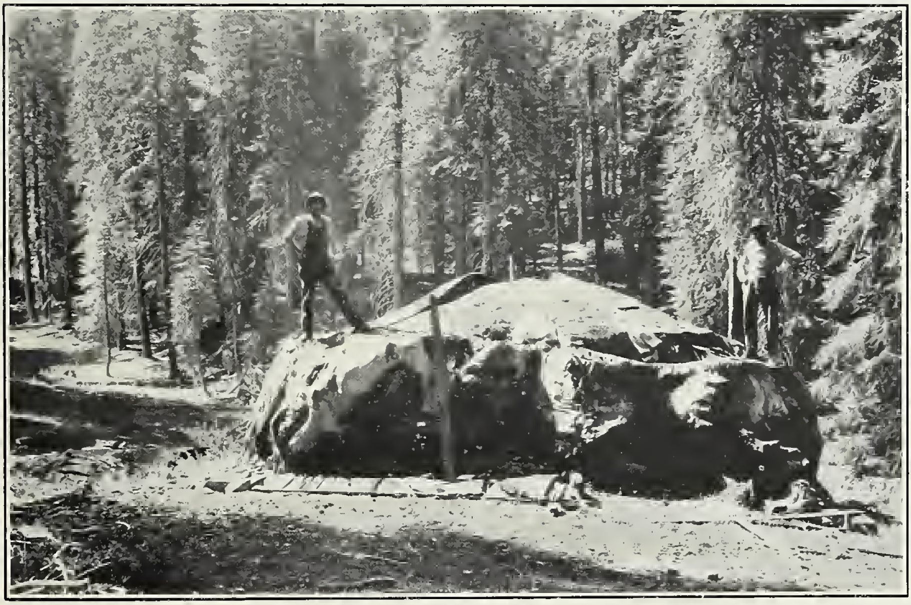
[2] Identification very nearly right.

[3] Not identified after 1130 A. D.

Leaving the vicinity of the General Grant National Park and going south to Porterville, thence by rail to Springville, a 3 days' trip was arranged to the old Enterprise millsite. Camp was made at the cabins, about 10 minutes' walk below the millsite. On going up from the camp, No. 23, known as the Centennial Stump, was found at once, as it is of enormous size, high in the center, and covered with names of visitors. It is located close beside the road and near the wash, about 100 yards from the clear space once occupied by the Enterprise Mill. The oldest tree which Huntington found at this locality had been

A

B



A. Cutting sample from stump, Enterprise: D–22, age 3000 years.
B. Centennial stump, Enterprise, Cut in 1874: D–23, age 3075 years.

numbered 116 in his lists. This stump had no number on it, but from the date of its cutting and its age of nearly 3,100 years, it is without doubt the one he refers to. The tree was cut in the winter of 1874–75 for exhibition at the Centennial. The trunk was hollowed out and prepared for transportation in pieces to Philadelphia, where it was said to have been erected, making a sort of hut. In consequence of the uneven surface left, it was very difficult to cut a sample from this stump. However, one was at last secured, which is 12 feet long as it lies on the table in the laboratory.

No. 22 was Huntington's No. 195 and grew near the center of the millsite. Its cutting was extremely easy and its cross-identification with No. 23 and the other trees farther north proved entirely reliable.

The location from which these two interesting trees were obtained is at the very top of a ridge with a steep descent on the east to the North Fork of the Middle Fork of the Tule River and a similar descent on the west to the Tule Valley. The top of the ridge is several hundred yards wide, with opportunity for considerable snow to collect there in winter. It receives little drainage from any source. Just north of it is Mount Moses, high and rugged, and to the south are high ridges extending toward Bear Valley.

All the sections obtained in these various trips were shipped to Tucson, and four weeks of continuous work were spent in cross-identification. All the identifications were satisfactory except the year 1580, which was finally determined by the special trip in 1919. The general method of measuring and marking these sections will be found in the next chapter and the tabulation of averages at the back of the book. Owing to the interest in these trees of remarkable size and age, a list of the 23 collected in these two trips is given in table 5.

IV. DETAILS OF CURVE PRODUCTION.

PREPARATION OF RADIAL SAMPLES.

Form of sample.—Nearly all of the 230 trees used in this investigation are represented by portions preserved in my collection. Wherever possible the entire section, 1 to 3 inches or more in thickness, was brought to the laboratory for examination. Unless the section was light and easily handled, it was found convenient to cut from it a radial piece showing the complete series of rings from center to bark. Naturally the enormous trees of the sequoia groups could be obtained only in radial form. The paper rubbings from Oregon and the small cuttings of the Prescott and second Flagstaff groups were also of this type. Hence the radial sample is regarded as the usual or type form in which the material appears in the laboratory. If the original section was small the radial piece appears as a bit of wood cut across the grain, square or triangular in cross-section and a foot, more or less, in length.

Method of Cutting.—The partial radials, such as used in the Prescott group, were secured from the stumps in place by making saw cuts at the edge of the stump in two directions, meeting a few inches below the surface. In this manner a piece of wood in the form of a triangular pyramid was secured and was sent to the laboratory. The radials of the sequoias were cut altogether from the tops of stumps or from the ends of logs that lay on the ground. From the manner in which the trees were cut down it was usually possible to get a clear surface of stump or log from the bark on one side to somewhat past the center where the under-cut had been made. After a minute examination of the surface exposed, a radius was selected which would give the greatest freedom from fire-scars and other irregularities of ring distribution. Two lines about 8 inches apart were drawn with blue chalk along this radius. Then two men with a saw 8 to 14 feet in length made a slanting cut on one of the lines of sufficient depth and in the right direction to meet a similar slanting cut from the other chalk line. In this way a long piece of wood of V-shape in cross-section was obtained, extending from the center to the outside and giving the full ring record.

In sequoias recently felled this cutting of the radials was extremely easy, but many of the sections obtained were from stumps which had been standing and weathering for 25 years and in one case 43 years. The exposure carbonizes the top of the stump and makes it extremely brittle and difficult to cut; small pieces break off and wedge the saw. Thus it often becomes a very difficult task to extract the radial section. The pieces into which the radial section breaks are marked for identification immediately, photographed and listed in notebook, and then carefully packed for shipment. On arriving at the laboratory, they are pieced together with the greatest care and then glued together in groups, making the entire radial section a series of convenient pieces about 2 to 3 feet in length.

Preparation for measurement.—These pieces were then examined to find the longest sequences of clear and large rings, and guide-lines for the subsequent identification and measurement were selected as nearly as possible perpendicular to the rings. Such lines having been decided on, two straight pencil lines, half an inch apart, were drawn and the surface between these was "shaved." For this purpose, after the trial of many other methods, a common safety-razor blade was clamped to a short brass handle. With this very sharp blade the rough surface of the wood is removed and the rings stand out very clear and distinct. Besides the space between the lines, the region close outside is usually shaved also for a preliminary trial at cross-identification, the final marks being the only ones permitted between the guide-lines.

The best light for observing the rings is a somewhat diffused light coming sharply from the side. A light falling on the wood perpendicularly is apt to be very poor, either for visual work or photography. Light from each side must be tried, for there is often a great difference between the two directions, due probably to the way in which the knife passed over the wood and bent the ragged edges of the cells. In photographing, the colors involved and the result sought (*i. e.*, to show the red rings as black) require an ordinary plate and a blue color-screen.

When the surface is well prepared it is placed in a suitable light and wet with kerosene applied by means of a bit of cotton on the end of a small stick. This deadens the undesired details of the surface, and brings the rings into greater prominence. The identified section is now supported over the unknown and with watchmaker's glass in eye and long needle in hand, the observer can make rapid comparison and quickly put on the required marks.

IDENTIFICATION OF RINGS.

In the early Flagstaff work the rings were first numbered, beginning at the outside without regard to the year in which they grew. But this was found to add complexity and involve the use of a separate reduction from the provisional numbers to the true dates of the rings. Accordingly the rings are dated at once as well as possible on some selected section that gives promise of an accurate record. The identification mark is a pin-prick or very small hole placed on the last ring of each decade. The middle year of each century has 2 pin-pricks and the centuries are marked with 3; the 1,000-year mark is 4. Marks found in error are "erased" by a scratch through them.

After the selected section is dated with the greatest care not to overlook or mistake any rings, others are dated by direct comparison with it. The common practical test in such comparison is the relation of width of a ring to its half-dozen near neighbors. For some unknown reason, rings of diminished size seem to carry more individuality than enlarged rings, and so they are usually picked out for cross-comparison.

In nearly every decade some are thus distinguished, and in each century there are usually 3 to 4 conspicuously small rings which give very important aid.

In the first work on the 2,200-year sequoia record, the identification was a laborious task involving all the writer's spare time for a year. The only real difficulty was with the ring for the year 1580. This was temporarily called 1580A, but the material collected in 1919 showed it to represent a year and a final and complete renumbering included it as such. In the end the comparisons gave entire confidence as to the identity of every ring. Section No. 2 gave the most nearly perfect long record, beginning at 274 B. C., and is used as a standard with which to compare all new ones.

The most difficult parts to identify are the compressed rings. Over long periods, varying from 5 or 10 up to 100 years, the rings are sometimes so crowded together that large numbers of them seem to be merged into one and their identification becomes extremely difficult and in a few cases impossible. The great variations in sizes so produced also exaggerate effects. These groups of compressed rings are considered as of little value, and in fact in many trees their measurement is omitted altogether. Tree No. 12 of the sequoias obtained from the Indian Basin had such bad groups of compressed rings that it proved practically impossible to identify them without a large expenditure of time not then available. Tree No. 17, also, from Camp 7, was found so full of compressed rings in the last few hundred years that all measurements were omitted after the year 1130 A. D.

Fire-scars.—Most of the big trees show fire-scars at some time in their history, and the process of the tree's regeneration is very interesting to observe. If the scar is small the woody growth quickly comes in from each side and covers it. If the scar is very large, occupying perhaps one-quarter or one-third of the circumference, the tree is likely never to recover and the burnt place remains permanently on its side. In cases of less extensive burns, the wood from each side year by year grows toward and over the injured spot, and if the injury has not been too great the approaching sides may meet and imprison their own bark within the tree. Thus one often sees the tops of the stumps marked here and there by a hole as large as a foot in diameter, filled with bark in perfectly good condition.

No. 12 had several fire-scars that interfered with the identification of rings. No. 18 also had one or two fire-scars and in particular showed a fire in the year 1781. The latter evidently stopped the growth at that point completely, yet was not large enough to interfere with recovery. In the sample in the laboratory the usual reddish-colored heartwood changes about the year 1700 to the white sapwood, which ends with the ring 1781 and shows a surface that was once covered with bark. However, immediately outside of that surface, the red heartwood begins again with the year 1791 in a thick, rapid growth. The heartwood continues for some 20 years before changing again into the white sapwood, which persists to the outside. In order to make sure that this gap would not prevent satisfactory identification, a small portion was cut from another part of the outside of the tree, showing some 300 rings without interruption; but this additional piece I found in that case to be unnecessary.

In sections numbered 22 and 23, from the old Enterprise millsite, there are injuries which do not greatly alter the appearance of the rings, yet are sufficiently great to weaken the wood and cause it to break at several points. If the break in such case is across the rings, it is easy to carry the identity of rings past the injured point. But when the break in any wood sample is all in one ring there may be a doubt as to whether the break is between two rings or in the middle of one. In the latter case there will apparently be an extra ring at that point. If the break is obviously between two complete rings, then an unknown number of rings may be lost at the broken point. The only way to carry the correct dating of the rings past such broken places is to secure samples from other parts of the same tree or from other trees, which show 100 to 200 rings on each side of the uncertain place without serious interruption. A simple cross-identification will show whether any rings are lost. However, in Nos. 22 and 23 just referred to, nearly all lines of breakage crossed the rings in a way that left no uncertainty. But No. 22 had an injury and a break between complete rings at about 1020 B. C. and a pronounced injury at about 1060 B. C. No. 23 had an extensive decayed place with the loss of about 35 rings at 1060 B. C. An extra piece cut from the stump of No. 23 carried the dating across these gaps with perfect satisfaction and in complete accord with No. 21 which had been secured 50 miles to the north.

Cross-identification between distant points.—The sequoias collected in 1915 had come from the immediate vicinity of Camp 6, about 7 miles east of Hume, and from Indian Basin, which is 3 to 4 miles north of Hume. The total extent of country covered was about 10 miles. All these were identified and found to be very similar in their characteristics. In 1918 the country represented was extended by sections from the new Camp 7, some 2 miles east of Camp 6. Nos. 20 and 21 were then obtained from the old Converse Hoist, 4 miles from Indian Basin and 15 miles from the Camp 7 district. Finally, 2 trees were obtained from the old Enterprise millsite, 50 miles from the other localities. It was realized at the time that there might be difficulties of cross-identification between these 2 trees at Enterprise and the other well-known and well-identified groups near Hume and the General Grant National Park. However, it was very gratifying to observe on close examination of these sections that no uncertainty was introduced in the identity of the rings. One realizes from this that, so far as sequoias are concerned, a distance of 50 miles between groups is likely to be no particular obstacle in cross-identification.

The difficult ring 1580.—The small ring 699 A. D. and several other difficult ones were absent in comparatively few trees and any uncertainty regarding them was removed in the early part of the work, but it was not so with the ring of the year 1580. The best of the tree records were from the uplands and usually omitted it, while many of the basin trees which showed it were at first very uncertain in identification. The ring was therefore provisionally called 1580A and held in doubt for several years. The question of its reality was finally settled in the affirmative by a special trip to the sequoias in 1919 and the collection of a dozen carefully selected radial samples. The final review of all the tree-records has resulted in satisfactory identification of some previously doubtful cases and in complete conviction regarding the ring for 1580 A. D. No other uncertain cases were discovered. Considering the 35 sequoia records now (1919) made use of, it seems possible that all errors of dating have been removed.

MEASURING.

Having prepared and identified the wood samples, the first method of measuring was to lay a steel rule on edge across the series of rings in a radial direction and to read off from the rule the position of the outside of every red ring. These were either recorded at once by the person measuring or were noted by a clerical assistant. This method applied to the Flagstaff and Prescott trees and to the European and Vermont groups. In nearly all of them the steel rule used was a meter in length. It was ascertained by tests that the errors in readings of this kind were less than 0.1 mm. on the average for a single reading. For the Oregon group a microscope slide was used with a vernier which gave at once readings to 0.01 mm. The readings obtained by either of these methods were recorded in two columns on a page, and the subtractions were performed afterwards, giving the actual width of the ring in millimeters and fractions. Thus any error in the original reading would affect two rings only. Very great numbers of readings have been done a second time and vast numbers have been checked over approximately; hence it is believed that errors of this kind are extremely rare; out of 20,000 measures, perhaps 4 or 5 have been discovered. Errors of subtraction may have occurred, but it is thought that these also are extremely rare indeed, since practically all of the work has been checked over a second time.

In the case of the sequoias, however, the method of measuring was much more highly developed. It required a cathetometer with a thread micrometer and adding machine. The cathetometer is placed horizontally on the table and the wood to be measured is also put horizontally on the table at a distance of about 33 inches. The cathetometer telescope has a lens of such a focus that 1 mm. on the wood section becomes 0.25 mm. in the focus. The micrometer has a screw-thread with a pitch of 0.25 mm., so that one revolution of the micrometer head moves the thread through exactly 1 mm. as seen on the wood. The individual measures of rings are made on the micrometer screw by reading the graduation of the head to revolutions and hundredths, giving directly millimeters and hundredths. On commencing a set of readings the stationary thread of the micrometer is first placed on the zero-year ring of each decade, and the reading of the cathetometer is made and this is entered on the adding machine. A space is then inserted on the adding machine and thereafter the micrometer reading of each ring in the decade is added in column as fast as made. Then another space is made on the adding machine and the total is entered without clearing the machine. Immediately below this total the reading of the cathetometer in the new position 10 years advanced is made and inserted on the machine without addition. Then another space on the machine is given, followed by the individual readings of the next decade. In this way all the years are read individually by the micrometer and every 10 years the sum of these readings is checked against the cathetometer reading, which should come to the same amount.

The reading of the micrometer screw to 0.01 mm. is closer than the average setting can be obtained. The rule has been generally observed that in every decade the agreement between the sum of the readings obtained and the cathetometer reading should check within 0.20 mm. In the earlier measures, where the rings were irregular or the surface of the wood uneven, this accuracy of check was not obtained in a few cases. Yet even there the error in checking was not much larger than the figure mentioned, and it is expected that the results are sufficiently close for all purposes desired. The 25,000 measures on the first group of sequoias were begun by the writer, but after 2,000 had been done they were continued by Mr. Edward H. Estill, who did them with great care. In the second group, with 22,000 rings, the measuring had been done by Mr. J. F. Freeman, who has made some slight alterations in the method above described by which an increased accuracy is obtained. As a result, the check between the decades by measure and by cathetometer is nearly always within 0.10 mm.

TABULATING.

The paper used for the tables throughout has been a cross-ruled paper with squares about three-eighths of an inch in size. This paper is 8 by 10 inches in size and suffices admirably for small tables. Usually 20 numbers are placed on a horizontal line with the beginning year at the left and with numbers from 1 to 20 at the top. Thus 1820, 1840, etc., will be placed at the left, and 1821 will be the first date given in that line. When it is desired to make longer tables, the pages are pasted together side by side or end to end, and then given a zigzag fold, so that two pages are open at once. In the case of the sequoias, with their 2,000 to 3,000 rings, no attempt has been made to paste the pages together, but enough loose sheets are used to cover the entire series at the rate of 20 years to a page. This gives sufficient vertical space to include all the necessary trees in a group and to use subgroups which may be summarized and averaged by themselves. An attempt has been made to check the addition of these numbers throughout.

AVERAGING.

In simple averaging the sums are placed in ink on the table and divided by the number of trees, using the slide rule for the process. There are several questions in connection with this subject. The first is whether straight averages of trees of widely different size give the best report of the evidence of the trees. It is evident that in taking averages of trees of mixed sizes the larger trees will carry more weight and their variations will be more pronounced in the result. But it is often the case that the smaller trees are the ones which show the greatest relative variations in the rings. This can be so much the case that the omission of a ring becomes a gross exaggeration. It is possible to use the relative values by taking the logarithm of each ring measure, averaging the logarithms, and then coming back to the number. This could be called a geometrical averaging, since it would be the equivalent of multiplying all the values together and then extracting the root equal to the number of values. In this way the small trees of the series would receive more importance. However, this plan is so long that it has not been used in practice.

One of the most common and puzzling problems is the proper method of handling the decrease in the number of trees in a group as the center is approached. A group of 5 may be selected, for example, and perhaps a century from the average center of the trees some one tree whose rings differ from the average may come to its end. It means that for 100 years near the center only 4 trees supply the data and at the point where the 5 change to 4 there is a discontinuity in the curve. In actual practice this lacking tree has usually been supplied by an extrapolation from its subsequent curve. That is, the variations assumed in the non-existent part of the tree follow precisely the variations in the remaining trees, altered to the average size of the missing tree by means of a constant factor, determined by overlapping periods. Thus, if 5 trees carried easily back to 1820, but only 4 of them extended to 1720, and it was desired to carry the full group to 1720, the period from 1820 to 1840 would be taken both for the 4 and for the 1 alone and the ratio between them determined. Now, averages for the 4 are carried back to 1720, and then the factor found in overlapping periods is applied to the mean of the 4, producing a probable value of the fifth between the years 1720 and 1820. This probable value is inserted in parenthesis in the table and all 5 values added up for an average. As a rule, groups are carried back only far enough to make assumed values of this kind a minimum in number.

There is one other problem in this immediate connection, namely, that of "gross rings." By gross rings I mean certain regions in a section where the average size of the rings becomes 2 to 5 times as great as normal. This is a problem by itself, both as to cause and as to method of treatment. Some study of its prevalence in different trees has been made, and it is usually safe to say that where an epoch is shown to have gross rings in one tree, the chances are at least even that the same years will have gross rings in the next tree. Since gross rings may not come oftener than once in several hundred years and last only 10 to 15 years, it is evident that we are dealing with something more than mere accident. The phenomenon probably has a climatic character. Yet, gross rings are not universal at any one time, and while one epoch may show gross rings in half the trees of a group it does not show it in the other half, judging by the groups examined. It is considered best to allow the ring values to enter the curves just as they are found, for while the gross rings disturb very greatly the size of a series of 10 to 20 rings, they do not seriously disturb the relation in size between a ring and its immediate neighbors. They therefore, as a rule, do not render the rings unidentifiable. It is likely, therefore, that they should be included in the means, and if some better way of handling them is discovered later it will not be difficult to apply it.

SMOOTHING.

In general the smoothing of a curve means removing some of the minor variations, so that the larger variations may be perceived. In the early part of the work the use of overlapping means was adopted. At the very start, overlapping means of a considerable number, such as 11 or 9, were used. This was quickly changed to overlapping means of 3. These overlapping means were done by the calculating machine (Brunswiga). On this machine three were added and then continuously the one next in sequence was added, while one at the other end of the three was dropped. However, this was changed to Hann's formula, because his formula is normally easier to apply and it gives a little more individuality to each observation. The method of applying Hann's formula consisted in adding to a table two columns consisting of, respectively, first and second intermediate values. This can be done rapidly and without taking too much space. To express the differences between overlapping means and Hann's formula graphically, we only need to say that if we take successive groups of three in any curve, forming a triangle, the center of gravity of the triangle is the value from overlapping means, but the point midway between the vertex and the middle of the base is the point from Hann's formula. In the present work Hann's formula has been used frequently, and in order to shorten description of processes the word "Hann" has been used as a verb.

In the analysis of curves already performed by the periodograph, the curves have sometimes been smoothed by Hann's formula before plotting and photographing. But a trifling error in the focus immediately smooths the curve, and therefore it is evident that the preliminary smoothing of a curve before plotting need not be done.[1] Such preliminary smoothing helps the eye to judge variations in the curve. The effect of out-of-focus position in a photograph may be called optical smoothing. It is evident that optical smoothing may be done in two directions, vertically and horizontally. In plotting a curve it is evident that the desired smoothing must be in a horizontal direction, but in the differential photographs made with the periodograph, the directions of optical smoothing may have a very important bearing on the judgment of the significance of the photograph. Of course, in the differential pattern, long interference fringes are sought and these are emphasized by optical smoothing parallel to them. Some illustrations of this will be given under the subject of the periodograph.

Perhaps no feature of this subject of tree-growth and climatic and solar variation has received more adverse comment than the matter of smoothing curves. The author is entirely open to conviction as to the advantage and disadvantage of such process, but it seems well to remember that our views as to this are likely to be a matter of convention rather than of actual thought in relation to the subject in hand. For instance, a monthly mean is a smoothed result. The rainfall, instead of being taken as it came, mostly in a few days, especially in the summer, is treated as if it were the same for every day in the month. Yearly means are smoothed values. The ordinary method of plotting yearly means is a smoothed representation of those quantities. The unsmoothed representation consists of what one may call a columnar plot. Examples of plots of that type may be found in connection with some rainfall records published by the United States Weather Bureau and in a representation of the London rainfall for more than 100 years published by the British Rainfall Association, and elsewhere. In this kind of plot the rain for a year is not represented by a dot, but by a block column which extends from the base-line up to the required amount and it has a width equal to the interval of one year according to the scale of the plot. Now, the ordinary way of representing rainfall places a dot at the middle of the top of this column, and these dots are connected together by straight lines. It is immediately seen that this cuts off each corner of the high column of any maximum year and contributes those corners to the adjacent lower column, so that the ordinary bent line of the rainfall record has thus been twice smoothed—once in the yearly sum and once in the method of plotting.

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[1] The three-score of curves which are now specially prepared for examination with the periodograph carry the mean values without smoothing.

In speaking of the above records, I have in mind the smoothing in time intervals, but I would like to note also that whenever a district is averaged as a whole the average thereof is a smoothing in space. The temperature at any one time in a city station is a single definite record; but if the mean temperature in a valley or a State, for example, is tabulated, there is at once a spacial smoothing. In the minds of many students of solar variation and weather, the reason why a large group of meteorologists fail to get evidence of the relationship is because they take the average of the whole earth at once in their test of temperature changes or of rainfall. It is evident, therefore, that the reason they do not get results is because they do too much smoothing of the curves. Studies in connection with the present investigation have given some indication that small districts balance each other in their reaction to solar stimuli.

STANDARDIZING.

The fundamental data tabulated in the appendix are the means of the actual measures of the various groups. They, therefore, contain the effects of the two chief arboreal constants, which are (1) the nearly universal big growth at the center of the tree and (2) the increased size in some entire trees due to specially favorable environment. In producing a perfectly normal record of tree-growth over long periods, one desires to have it expressed throughout in terms of the normal adult growth of an average tree. This is the kind of record most suitable for analytical study. In the present study, in which so much time has been spent in finding how the work should be done, on account of the great labor involved no attempt has been made to apply these corrections to individual trees; but in comparing groups with one another it has seemed worth while to apply both corrections in a simple manner. Each group supplies an approximate curve of its decreasing growth with age. So, after plotting the means, a long average line as nearly straight as possible is drawn through them. This gives the factor by which individual rings may be reduced to the standard adult growth; at the same time this line enables us to reduce the different groups to a common standard of size. Both corrections are done at once by calculating for each year the percentage departure of the plotted mean from this line. In actual tabulation this works out very easily, for under each mean is placed the reading of this line, and below that the quotient obtained by dividing the former by the latter. The line of quotients then becomes the desired group curve corrected for age and for mixed sizes. This process is the standardizing process referred to in previous descriptions.

PLOTTING.

So many curves have been made in connection with this study that a practically uniform system throughout has been adopted. The paper used is a cross-section paper with the smallest divisions 2 mm. in extent and with heavy lines at every centimeter. The smallest divisions are uniformly used for one year unless in some special study. For the illustrations, these plots are traced and drawings made from which the engravings are reproduced. For use in the periodograph, the plot is made on the same scale and continued in length to any amount up to about 40 inches. The space between the base-line and the curve has then been cut through with a sharp knife, usually a razor blade, and the curves have been mounted in long strips some 4 inches wide and 50 inches long, and the backs painted with opaque paint. In this way they are mounted for analysis. A mirror behind reflects light of the sky overhead through the curve and supplies the necessary illumination for photography.

Problems in plotting.—In connection with the plotting of the curves used in this study, certain problems have arisen which seem worthy of consideration. The ordinary plot and the ordinary averaging seem extremely good and appropriate when the variations are small in comparison with the mean values, but when the variations are large in comparison with the mean values it does not seem to the writer certain that the usual plotting conveys an accurate idea or gives a suitable basis for further work. This may be illustrated by the plotting of rainfall. If the rainfall doubles in some unusual year, it produces an immensely greater change in the area of the curve than when it goes to one-half of the mean. Doubling the mean produces the same changes as going down to zero, though in proportion the latter is infinitely greater.

The enormous exaggeration, therefore, of excessive rain values was felt to introduce misleading material in the ordinary form of a plot. In order to overcome this at least one experiment has been made with what is called a bilateral plot. In this the quantities from 0 to 100 per cent of the mean are plotted as before, but the quantities over 100 per cent of the mean are inverted in percentage and plotted above the mean line on an inverted scale. It is recognized that this is not the perfect way of making a plot of this sort, for by this plan the mean value of the new curve will not be at the same point as before, but will be somewhat below it. However, the matter is only in the experimental stage and it has not been thought necessary to work out a correct procedure.

V. CORRELATION WITH RAINFALL.

Result of study of curves.—On completing numerous curves of tree-growth in the manner already described, three characteristics were observed: (1) in arid-climate groups the annual rings are approximately proportional to rainfall; (2) in moist-climate groups they vary with the changes of solar activity; (3) in each they are subject to certain cycles or periodic variation. The first of these is the subject of the present chapter.

Early tests of rainfall correlation.—The earliest comparison with rainfall in this investigation was made between the first Flagstaff subgroup of 6 trees and 43 years of precipitation records at Prescott, 67 miles distant. It was not expected that agreement in individual years would be found; accordingly smoothed curves were used, consisting of overlapping means of 9-year groups. This produced curves of gentle variation, but similarity in the curves was evident. These early curves are presented in figure 13. The best agreement was found by placing each mean of 9 years of rainfall at the end of the 9 years as in this figure instead of in its center. This lag of four years seemed inconsistent with the later results of yearly agreement without lag, and in fact for years it has been accepted with some hesitation by the writer. Yet in the present consideration of the subject it appears to have a special significance. This existence of the lag in long periods agrees in principle with the "accumulated moisture" effects observed in the Prescott trees and with the idea of a tree exhibiting a reserve power or vitality which may run low or be built up by varying environment. The principle will be referred to again below; it is sufficient now to state that it seems quite reasonable to find no lag in yearly correlation with rainfall and at the same time a very considerable lag in the slower variations.

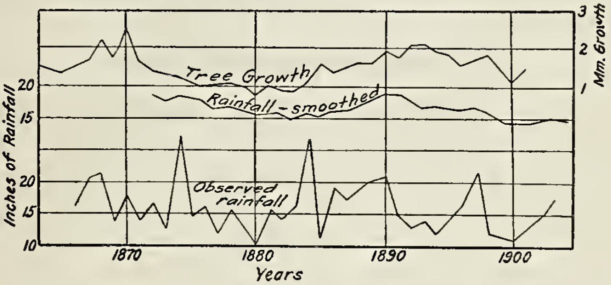


FIG. 13.—Correlation between tree-growth and rainfall in smoothed curves; Flagstaff.

The comparison in figure 13 was made with Prescott records because there were not at that time enough Flagstaff records to be of service. But later, when a Weather Bureau station had been established in Flagstaff for several years, the striking comparison shown in figure 14 was made. In this the lower curve represents the average annual growth of 25 trees and the upper curve is the precipitation 12 miles distant. The latter is taken from November 1 to November 1 in order to carry the snowfall into the following season of growth. This study suggested the investigation of the time of year to begin annual means of rainfall, which has already been presented in Chapter II. Figure 4 gives a comparison between Flagstaff rain and the two Flagstaff groups, and also shows how the best time of beginning the year was determined. It proved to be November 1 at Flagstaff and September 1 at Prescott, where the nature of the ground gives more chance of conserving moisture. The great difference between individual trees in response to rain is also shown in figure 5. It is evident that quick-growing trees serve as better indicators.

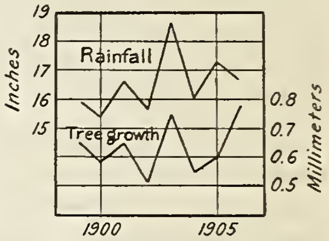


Fig. 14.—Early test of correlation between tree-growth and rainfall by years; Flagstaff.

THE PRESCOTT CORRELATION.

Five subgroups, numbering in all 67 trees, were obtained from different points in the vicinity of Prescott. These all cross-identified among themselves with entire success, both as individuals and as groups. The group curves are shown in figures 6 and 7, but in comparison with the Prescott rainfall they differed greatly, the group nearest the city showing much the best accordance. Accordingly this group is plotted by itself in figures 7 and 15 with the rainfall curve. On the whole there is much agreement, as may be seen by comparing the crests and troughs of one with those of the other. The most conspicuous discrepancy is in 1886, where the rainfall decreases and the growth of the trees increases. In 1873 the growth seems to have responded to the decrease in rainfall, but to a greatly diminished degree. The tree maximum of 1875, one year behind the extreme maximum of 1874 in the rainfall, is entirely reasonable, since the ground may become so saturated that the effects last until the following year. On the whole, the curves shown in figure 7 support the idea of a proportional relation between annual rainfall and annual growth.

Accuracy.—The accuracy with which the pine trees near Prescott represent the rainfall recorded in that city for 43 years is, without correction, about 70 per cent. By a provisional correction for conservation of moisture by the soil this accuracy rises to about 82 per cent. The nature of this conservation correction is very simple; it makes use of the "accumulated moisture" of the meteorologist. It signifies that the rings in these dry-climate trees vary not merely in proportion to the rainfall of the year, but also in proportion to the sum of the profits and losses of the preceding years. The "credit balance" in their books at the beginning of the year has only somewhat less importance than the income during the current year.

Mathematical relation of rainfall and growth.—In order to formulate the relation between rainfall and tree-growth, an effort was made to construct a mathematical formula for calculating the annual growth of trees when the rainfall is known. Any such formula must perform three principal functions: (1) reduce the mean rainfall to the mean tree-growth; (2) provide a correction to offset the decreasing growth with increasing age of the tree; and (3) express the degree of conservation by which the rain of any one year has an influence for several years. In a formula of universal application other factors will play a part, but for a limited group of trees in one locality they can be neglected.

The first process, namely, the reduction of the mean rainfall to the mean tree-growth, is a division by 250. This is the general factor K in the formula below. The second part, namely, the correction for the age of the tree, was practically omitted in forming the curves shown, since judging by the Flagstaff curves its effect would be very slight in the interval under discussion. In long periods it is an immensely important correction and its effect should always be investigated. Over the short periods used in this rainfall discussion the decrease of annual growth with age may be regarded as linear and an approximate formula is

$$\frac{G_n}{G_y}=1-c(n-y)$$

Where G_n represents growth in any year n; G_y is growth in middle year of series y, and c is the rate of change per year, a constant which was 0.0043 in the last half century of the Flagstaff series. Over the whole interval from 1700 to 1900, in the first Flagstaff curve, the growth was approximately an inverse proportion to the square root of the time elapsed since the year 1690 and may be closely expressed in millimeters by the formula

$$T_n=\frac{10}{\sqrt{n-1690}}$$

T_n is here the mean tree-growth for the year n. If G be the mean size of rings, then the factor to be introduced in a general formula becomes

$$\frac{10}{G\sqrt{n-1690}}$$

Character of the conservation term.—This factor has two important features: (1) in this arid climate it applies better as a coefficient than as an additive term, and (2) it gives a prominent place to "accumulated moisture" as commonly used in meteorology.

The first assumption in regard to conservation was that the ring-growth in any one year was built up by contributions from the current year and previous years in diminishing proportion. For example, it would be proportional to

$$R_n + \tfrac{1}{2}R_{n-1} + \tfrac{1}{4}R_{n-2} \text{ etc.}$$

in which R_n is the rainfall for the current year, R_{n-1} that for the year preceding, etc. This may be called an additive correction. It did not give satisfactory results for the Prescott trees, although a formula of this general type has been applied with some success to the sequoia, which grows in more moist soil.

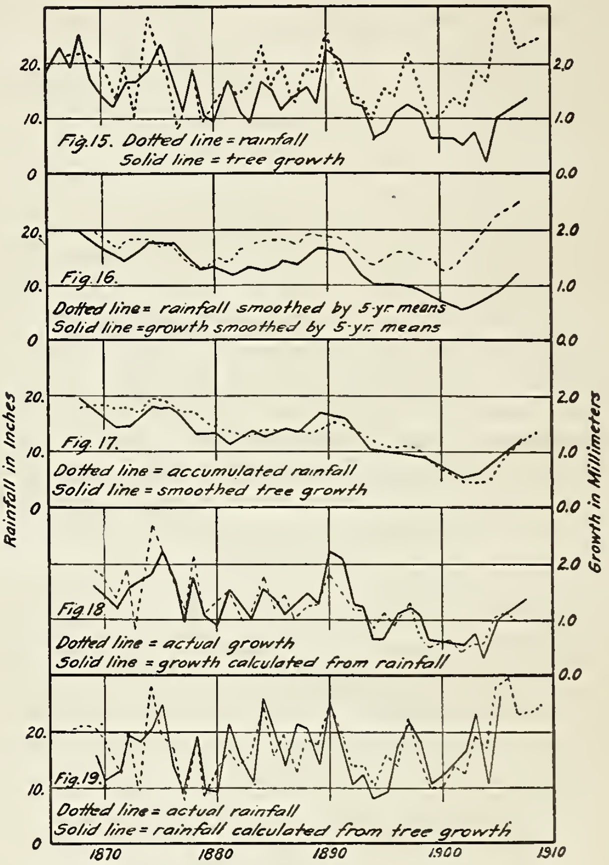


Fig. 15.—Relation of tree-growth and rainfall at Prescott, Arizona. Tree-growth and rainfall uncorrected.
Fig. 16.—Five-year smoothed curves of growth and rainfall.
Fig. 17.—Accumulated rain and smoothed tree-growth.
Fig. 18.—Actual tree-growth and growth calculated from rain.
Fig. 19.—Actual rain and rain calculated from tree-growth.

The variations in the Prescott trees were seen to be proportional both to the rainfall of the year and to the average growth or activity which the trees had exhibited in the preceding few years. But this average growth bore the same relation to the average or smoothed rainfall that the accumulated moisture bore to the smoothed rainfall. Hence the ratio between accumulated moisture and smoothed rainfall gave at once the required ratio between smoothed tree-growth and smoothed rainfall. These relations are shown in figures 16 and 17.

Accumulated moisture is simply the algebraic sum of the amounts by which all the years in a series from the start to and including the year desired depart from the mean. It may be expressed by a formula, thus

$$A_n = (R_1 - M) + (R_2 - M) + \dots . (R_n - M) = R_1 + R_2 + R_3 + \dots R_n - nM$$

and conversely

$$R_n = M + A_n - A_{n-1}$$

In this formula A_n is the accumluated moisture for the nth year of a series of consecutive years whose mean rainfall is M.

The simple empirical formula for the tree-growth T_n for the nth year of this series thus was found to be:

$$T_n = K \,.\, \frac{cM + dA_n}{S_n} \,.\, R_n$$

in which c and d are small constants found advantageous in reducing the accumulated moisture curve to proper scale. S_n is the reading of the smoothed rainfall curve and the term $cM + d\,A_n$ is the accumulated moisture expressed in values above a base-line instead of departures from a mean. In actual numbers this becomes

$$T_n(\text{in inches}) = \frac{1}{250} \,.\, \frac{0.90\,M + \frac{1}{4}\,A_n}{S_n} \,.\, R_n(\text{in inches})$$

The mean value of the rainfall M is 17.1 inches. The application of this formula in calculating tree-growth at Prescott from the rainfall is shown in figure 18.

The reversal of the process in order to ascertain rainfall from tree-growth seems to be fully as accurate over this limited period, and its result is shown in figure 19, where the curve has an average accuracy of 82 per cent for individual years. In producing this reversal the following operations were performed:

1. A 5-year smoothed curve was made of the tree-growth. This gives us the term $\frac{0.90M + \frac{1}{4}A_n}{250}$ in the reversed formula

$$R_n = \frac{S_n}{\frac{0.90M + \frac{1}{4}A_n}{250}} \,.\, T_n$$

2. This term is multiplied by 1,000 and $3.6M$ subtracted, leaving A_n in inches.

3. From A_n an approximate R_n is found by the formula

$$R_n = M + A_n - A_{n-1}$$

4. This series of approximate rainfall R_n is smoothed and becomes the S_n of the formula.

5. Final values are then found by the proportion

$$\frac{0.90M + \frac{1}{4}A_n}{250} : S_n :: T_n : R_n$$

It should be emphasized that the above formula for conservation is the one found to apply under dry climatic conditions. In moist climates the trees, so far as observed, seem to depend on other meteorological elements or combinations of elements.

The Prescott trees, as we have seen, even without correction give a record of rainfall with an accuracy of about 70 per cent. It is possible that the Flagstaff trees with their higher elevation, more certain rainfall, and more central location in the zone occupied by this species give somewhat more accurate records. They are probably much less often subjected to extremes of dryness, which throw the tree out of its equilibrium and cause it to produce an abnormally small set of rings. It seems likely, also, that the less compact soil, combined with a more abundant precipitation, produces a yearly growth more nearly proportional to the rainfall than at Prescott.

Summary.—In considering this reduction it seems fairly clear that (1) there is a strong correlation between rainfall and tree-growth; (2) the accuracy may be increased by introducing a conservation correction; (3) in dry soils this factor enters as a coefficient; (4) this coefficient depends on the state of activity of the tree; (5) in the Prescott trees this state of activity follows the curve of accumulated moisture.

Although the moisture-content of apparently dry ground may be a most important item, it is by no means certain that the observed accumulated moisture effects consist in actual moisture in the ground. It may be that they represent some vital condition of the tree. The matter is a very interesting one for future study.

Sequoia correlation with rainfall.—On his return from the big trees in 1912, Professor Huntington supplied me with a curve of sequoia growth obtained from many comparatively young trees which had been cut in the lower edge of Redwood Basin near Camp 6. On comparing these with his curve of rainfall in the San Joaquin Valley, compiled from records at Fresno and San Francisco, a close relation was not evident, but an additive formula

$$T_n = k \cdot \frac{R_n^2 + R_{n-1}^2 + R_{n-2}^2}{R_n + R_{n-1} + R_{n-2}}$$

was used with encouraging results. This formula was designed to allow for strong conservation in the soil, not of the static type as in a pond, but of the moving type, as if a belated supply from the snows came to hand and then passed on. The tree was assumed to receive moisture from the current year and from the first and second preceding years; and whichever of the three was greater, that one had the more effect. The application of this formula is shown in figure 20.

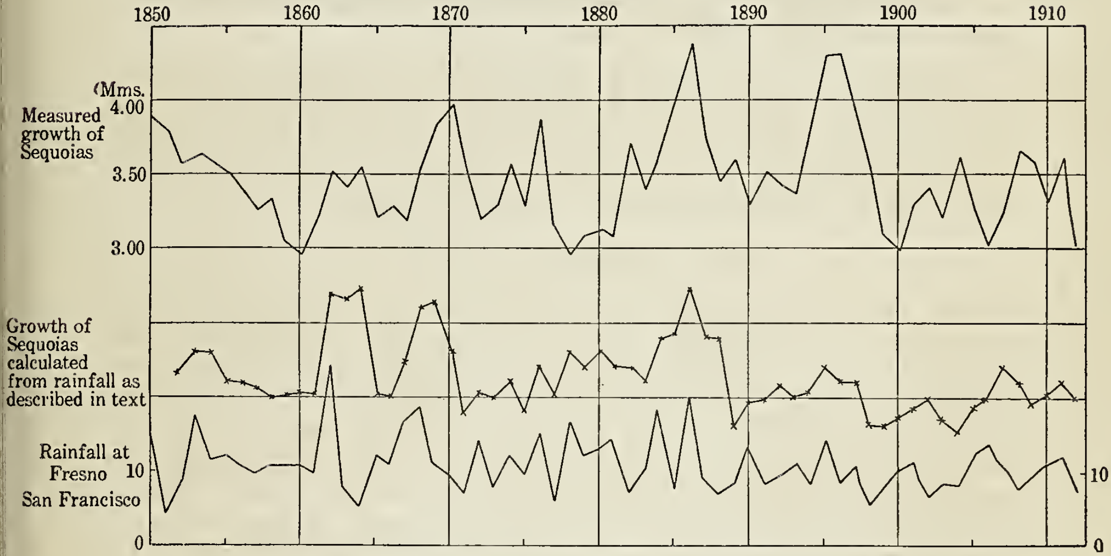


Fig. 20.—Huntington's early curves of sequoia-growth and rainfall compared with growth calculated by a conservation formula.

But on identifying the rings in the trees collected from that locality in 1915, and especially on finding the soft, delicate parts of the 1915 ring on D–5, it seemed fairly certain that the curve of growth given in figure 20 is one year in error through the omission of a final ring. The growth, then, which appeared to be 1902, for example, and for which a pronounced conservation was necessary, really came the year before,

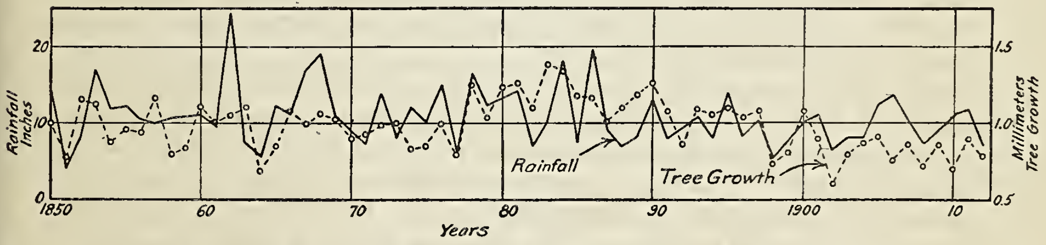


Fig. 21.—Comparison of Fresno rainfall (after Huntington) and sequoias D–1 to 5.

and less conservation or none was needed. The comparison of the same rainfall curve with the old sequoias of the present series is given in figure 21. In this the agreement is not as good as at Prescott, but there is marked similarity in many details. My curve from very old trees is probably not as good in details as Huntington's samples from young and sensitive trees. His material is well worth cross-identifying and dating with care, and then comparing with any records of snowfall which can be obtained from the sequoia groves. It is greatly to be regretted that Fresno, 65 miles away and at 5,000 feet lower elevation, is the nearest point where precipitation records can be obtained for a period long enough to be of value.

Future work.—It will be very interesting to find whether the characteristics of the correlation at Prescott are general in arid climates and dry soils and whether practical formulas for conservation in moist soils or climates can be worked out. When this is done the significance of the study of annual rings will be greatly increased.

METEOROLOGICAL DISTRICTS.

The study above described raised emphatically the question as to the extent of the region or district from which comparative rain records should be selected. Such a meteorological district could be defined as one in which homogeneous weather elements are found. But we immediately ask ourselves the questions: must all weather elements be alike in it or is it sufficient to have only rainfall (for example) essentially the same throughout; will the district remain constant through indefinite time or will it change; is the district for short-period weather changes the same as the district covered by secular changes. In the present discussion I have understood by meteorological districts such regions as may show similar or identical variations in some one weather element. It seems likely that a region which may show unity in small or rapid variations may not do so in large and slow variations, or more likely may be a small fraction of a region which will show unity in large variations.

Meteorological districts and growth of trees.—The cross-identification of trees over large areas has already suggested the use of annual rings as a possible aid in delineating meteorological districts. This function of the rings has received some exemplification in the present study. For instance, the pine trees of Norway differed in such a way that it was necessary to divide them into two classes, one of which came from the outer coast near sea-level and the other from the inner fjords and mountains. The trees from these different regions show strong reversal with reference to each other. Again, the trees from the lowlands about the Baltic Sea show marked similarity in their variations and indicate, as we would expect, a homogeneous district. Furthermore, groups from near the Alps show strong differences from the other European groups, as we might expect from our experience with the five groups from the mountainous country about Prescott. A rugged and mountainous region is very difficult to divide satisfactorily into meteorological districts. Yet, in spite of local differences, mountain regions may be alike in major characteristics, for all the Prescott groups, though differing among themselves, cross-identify excellently with the Flagstaff trees 60 miles away. The sequoias also cross-identify perfectly in mountain localities 50 miles apart, showing that there is enough similarity in different parts of the high Sierras to cause the trees to agree in many variations.

Arizona and California.—Fully 450 miles intervene between the sequoias of California and the pines of Arizona, yet there are strong points of identity between them in the last 300 years. The dates of notably small rings are much alike in each. The details of this comparison have not yet been fully studied, but they support the idea long since expressed (1909) that Arizona and California, especially its southern half, form parts of a large district which has similarity in certain variations. A long acquaintance with this region throws light on the details of this similarity. The winter precipitation, which is largely in the form of snow at the altitude of the trees studied, has the major influence on tree-growth, for it is largely conserved near the trees, whereas the summer rains are usually torrential and the water quickly flows away. The winter storms moving in an easterly direction reach the coast region first and after about 24 hours are felt in Arizona. Thus, in spite of the coast range of mountains and the intervening low-level deserts, each winter storm passes over both regions and causes an evident similarity between them. In a large view they belong to a single meteorological district.

Meteorological districts and solar correlation.—In searching for a link of connection between solar variation and meteorological changes, we must bear in mind the effect of possible reversals in neighboring meteorological districts, such as noted above in Norway. It may be the lack of such precaution which has caused many meteorologists to condemn at once the suggested connection between the distant cause and the nearby effect. We must remember that districts may be small in area, and in combining many together we may neutralize the result for which we are in search. Some illustration of correlation found in small districts will be given in the final chapter.

VI. CORRELATION WITH SUNSPOTS.

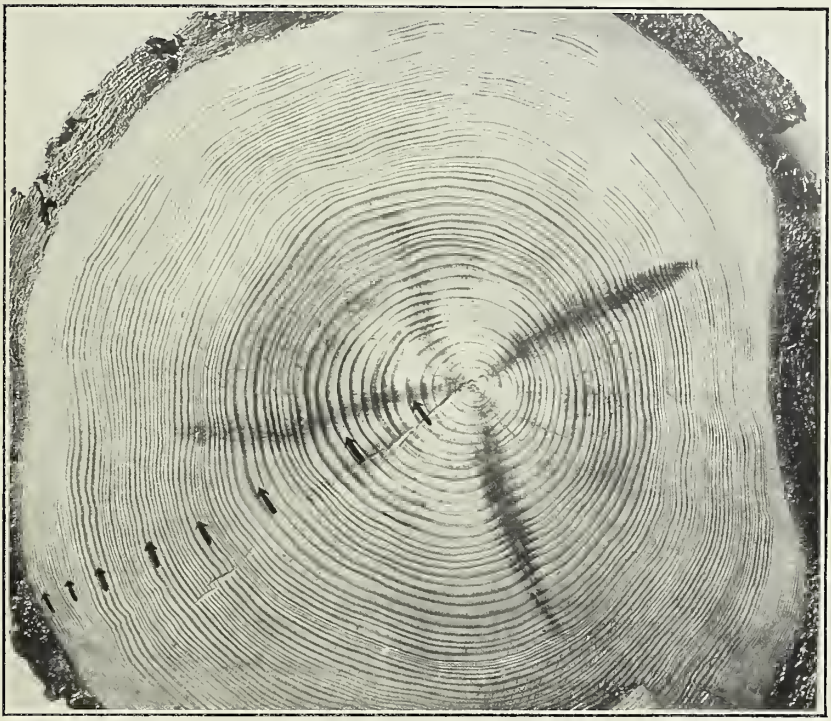
Dry-climate tests.—In the work of 1907 (published 1909) upon the first group of 25 yellow pines from 1700 to 1900 A. D., several long sequences of variation in a 5 to 6 year period were noted. These were compared with rainfall records at Prescott and in southern California and the crests of rainfall and growth appeared to coincide in date. It was then seen that the temperature curve of southern California had a period and phase corresponding to the rainfall curve, but with the second minimum almost entirely suppressed, and that finally this temperature curve resembled in form and phase the inverted curve of sunspot numbers. In connection with the publication referred to (1909), a set of curves was prepared to show these relationships. This set is partly reproduced in figure 34, page 104. In the original drawing the tree-curve was the least satisfactory, which was to be expected, as no real certainty in the dating of rings existed at that time. After cross-identification the tree-curve was again integrated for the 11-year period and far better results were obtained. This new curve is given in the figure referred to.

This type of integrated curve gives many facts in a very condensed form. A differential or detailed form of presentation should accompany it, as in figure 25, showing the full series of individual observations and beside it the curve with which it is to be compared. The differential study of the Arizona trees will be taken up in connection with cycles, but can be summarized in the statement that in the last 160 years 10 of the 14 sunspot maxima and minima have been followed about four years later by pronounced maxima and minima in the tree-growth. Also, during some 250 years of the early growth of these trees, they show a strongly marked double-crested 11-year variation.

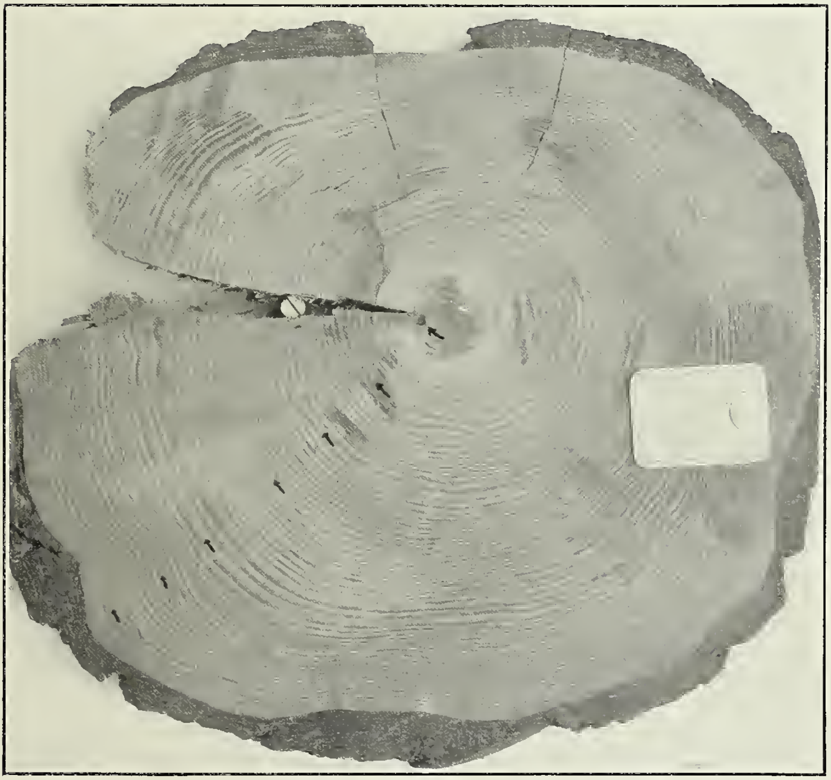
Wet-climate reaction.—In the very first group of continental trees studied, those obtained at Eberswalde near Berlin, the remarkable fact was recognized at once that 13 trees from one of those carefully tended German forests show the 11-year sunspot curve since 1830 with accuracy. The variation in the trees is shown in plate 8. The arrows on the photographs are not to call attention to the larger growth, but to mark the years of maximum sunspots. The other trees of that group do not show quite so perfect rhythm as do the marked radii shown, but are like the other parts of these sections, showing strongly a majority of the maxima. Taking the group as a whole, the agreement is highly conspicuous, and the maximum growth comes within 0.6 year of the sunspot maximum. The Eberswalde curves arranged in two groups and compared with the sunspot curve were shown in figure 9, page 38.

In the group of six sections from south Sweden, which were measured subsequently in Stockholm, a spruce (*Picea excelsa*) was discovered which shows the sunspot rhythm with the same striking clarity as the

A



B



A. Section of Scotch pine from Eberswalde, Prussia, showing solar rhythm.
B. Another section from the same forest, showing same rhythm.

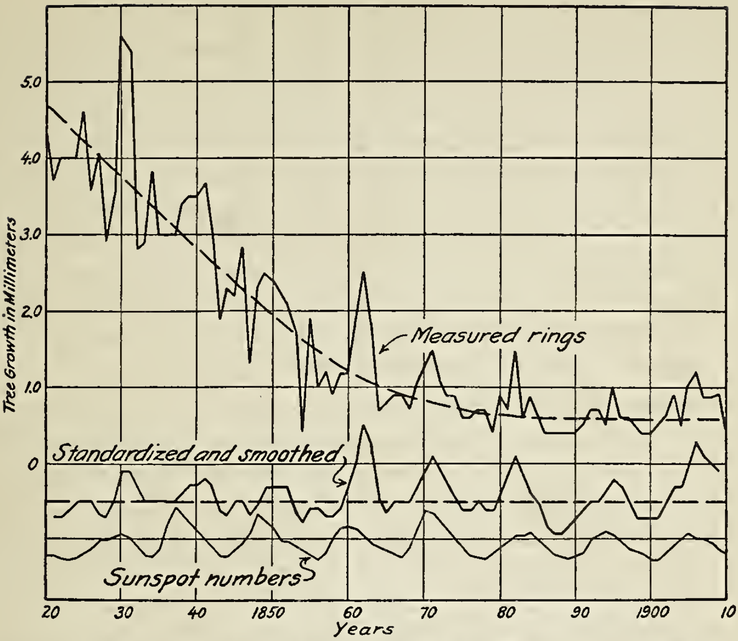


FIG. 22.—Sunspot numbers and annual rings in spruce tree from south Sweden.

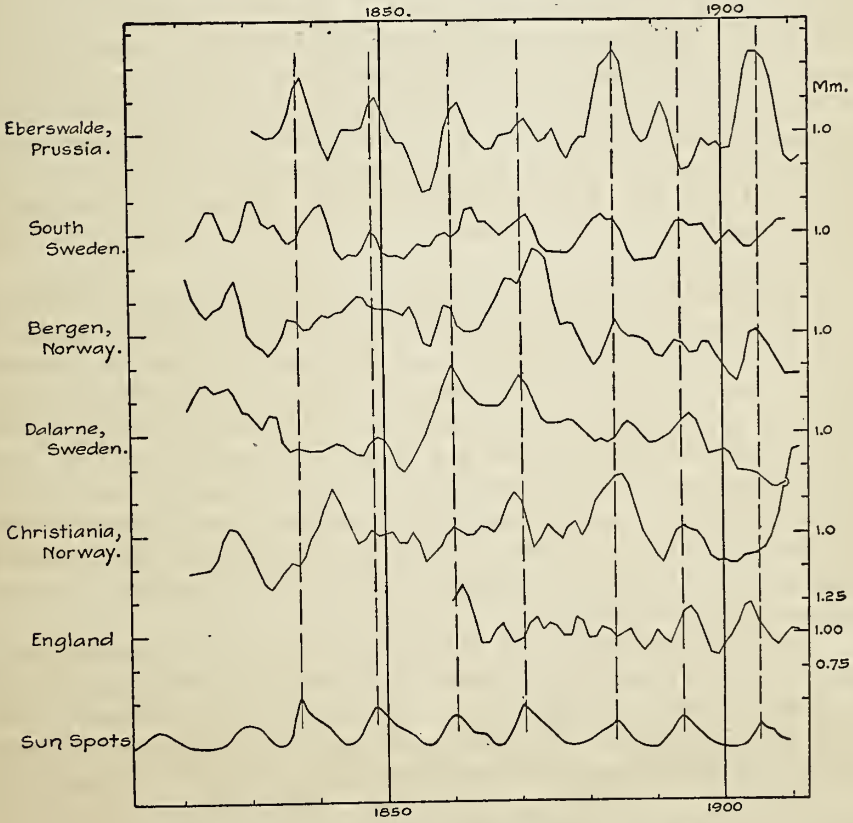


FIG. 23.—Six European groups, standardized and smoothed.

best Eberswalde sections. In view of the as yet unsuccessful efforts to obtain a photograph of this section, its measures have been plotted and are found in figure 22 with the sunspot curve for comparison. In the figure the upper curve gives the actual measures with the standardizing line drawn through them. The middle curve shows the same measures reduced to percentage departures from the line and smoothed by Hann's formula. The lowest curve shows the corresponding sunspot numbers. It would be highly interesting to know the exact conditions under which a tree produced such a curve of growth as this. In the opinion of the writer, it would not be impossible to find other trees of this type, and even to identify them without real injury to the tree, so that surrounding conditions could be studied.

The European groups.—For better comparison, the nine European groups have been corrected for change of growth-rate with age, reduced to percentages of their own means, smoothed by Hann's formula, and plotted in figures 23 and 24 together with the sunspot curve. They do not all follow the sunspot numbers with equal accuracy, and the six groups showing best agreement are segregated in the first of the two figures. The north German and south Sweden groups around the Baltic Sea are the most satisfactory; the group from the west coast of Norway is almost as good. Then come the Dalarne, Christiania, and south of England groups. These six in figure 23 have the times of sunspot maxima indicated by broken lines carried straight upward from the sunspot curve at the bottom. Of the other three groups, the trees from the inner coast of Norway as a whole appear to show a reversed cycle, probably because they were in deep inland valleys, while the southern groups, northwest Austria, and southern Bavaria close to the Alps have combined agreement and disagreement, so that they can not as yet be considered to give a definite result. They are shown by themselves in figure 24.

However, in the 6 groups representing the triangle between England, northern Germany, and the lower Scandinavian peninsula, a variation in growth since 1820 showing pronounced agreement with the sunspot curve is unmistakable. Every sunspot maximum and minimum since that date appears in the trees with an average variation of 20 per cent. This is shown in figure 25, which contains the mean of the 57 trees of the six groups, with the sunspot curve placed below for comparison. The agreement is at once evident. The apparent increase of tree-growth with increase in the number of sunspots becomes still more striking when the means are summated in a period of 11.4 years, as shown in the lower part of the figure.

A second important feature of figure 25 is that five of the eight minima show a small and brief increase in tree-growth. This suggestion of a second maximum is of interest, because in it we find agreement with Hann and Hellmann in their studies of European rainfall and sunspots, and it lends added weight to results which each author obtained but which neither allowed himself to regard as conclusive. In the immense work of Hellmann (1906) upon the rainfall of the North German drainage area, it is this inconspicuous maximum which he finds the more important of the two.

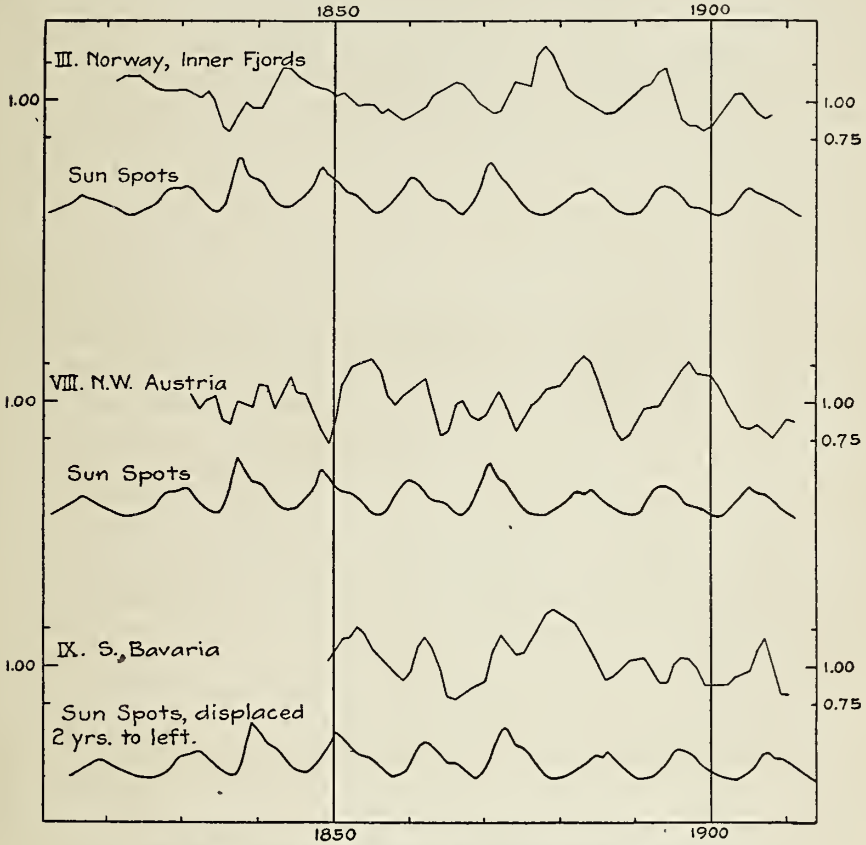


FIG. 24.—Three European groups, standardized and smoothed.

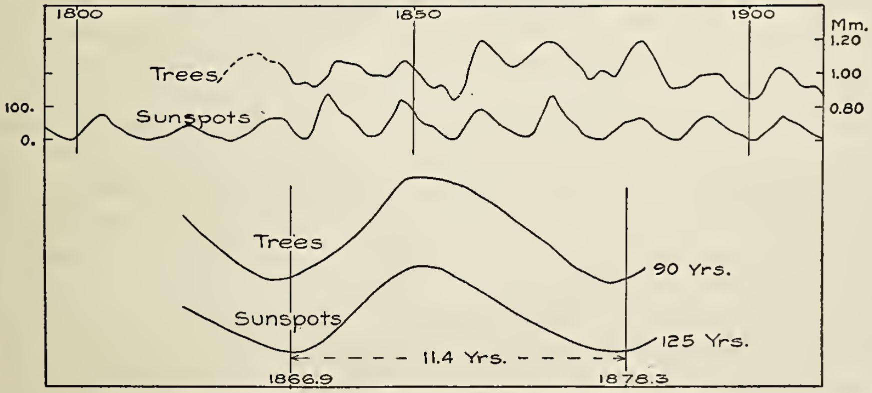


FIG. 25.—Comparison between 57 north Europe trees (smoothed) and sunspot numbers. The trees are from England, Norway, Sweden, and north Germany.

In seeking further evidence of sunspot correlation, advantage was taken of certain statistics recorded while measuring the various sections. Before making the measures or identifying the rings in any way, the groups of rings larger than the average were sought out and

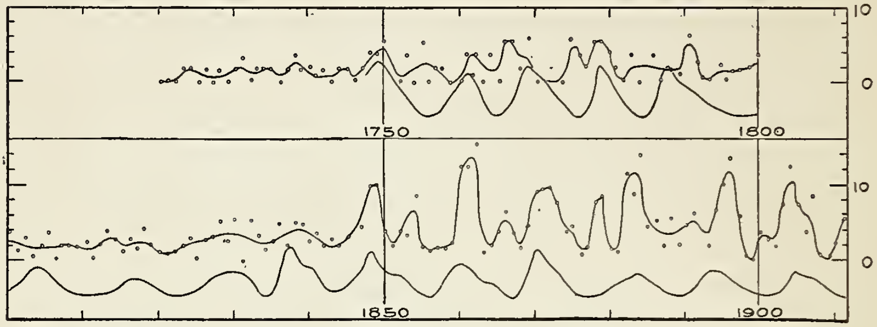


Fig. 26.—Dates of large rings in 80 European trees compared with sunspot curves. Ordinates give number of trees in total of 80 showing maxima in respective years.

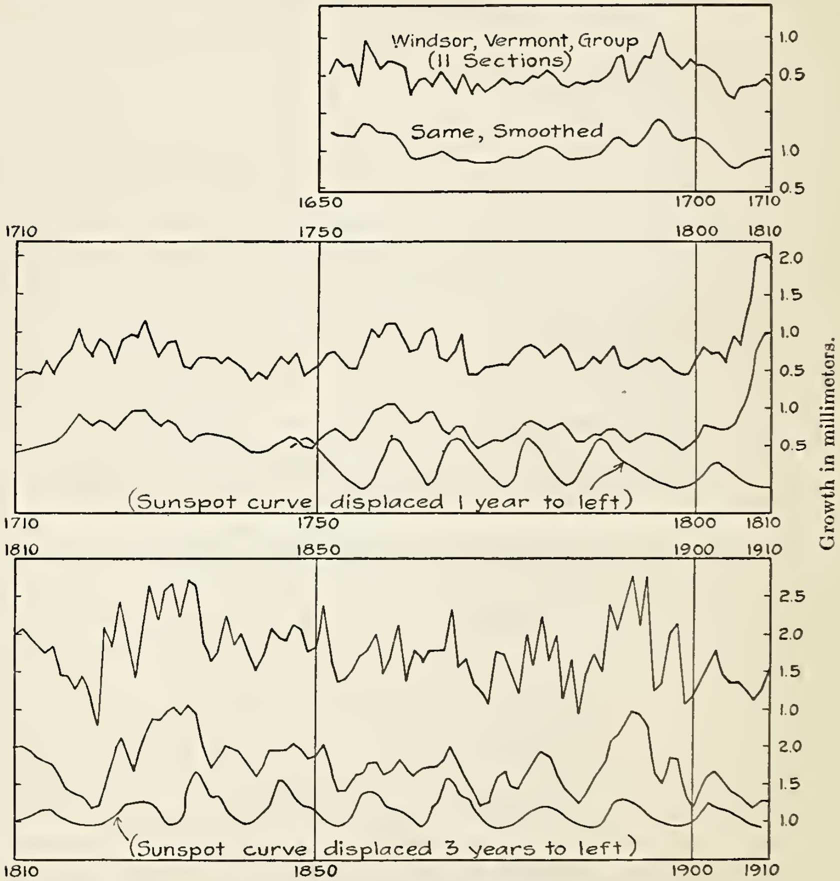


Fig. 27.—Tree-growth at Windsor, Vermont, showing measures uncorrected; same standardized and smoothed, and sunspot numbers displaced 3 years to left.

crosses were placed upon the central ring, which was usually the largest of the group. These crosses are well shown in plate 4, B. Their dates were noted during the measuring. In figure 26 the ordinates give the number of maximum marks found in each date throughout the whole

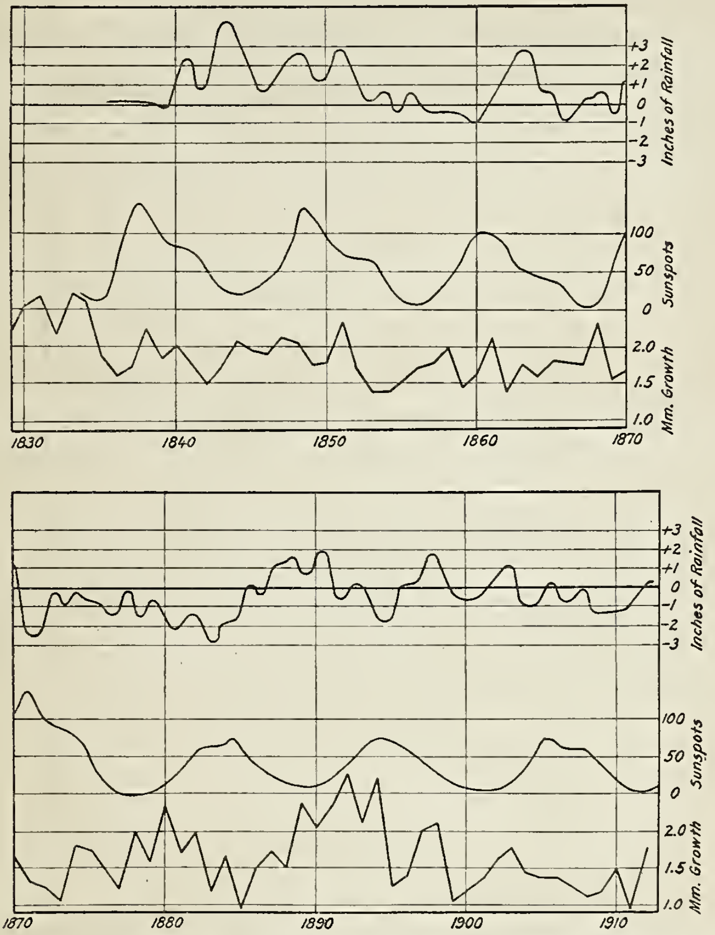


FIG. 28.—Smoothed quarterly rainfall (upper curve), sunspot numbers (center), and tree growth (lower) at Windsor, Vermont, 1835 to 1912.

80 sections. The more recent dates show higher crests because there are more trees. In the second line is the sunspot curve. The matching of the crests of the two curves is unmistakable. The secondary tree-crest at sunspot minimum is very regular, as would be expected from the inclusion of the three groups of figure 24, some of which are evident reversals. This test is only qualitative, but seems to the writer to offer substantial support to the quantitative relation shown in figure 25.

Windsor (Vermont) correlation.—An interesting sidelight is thrown on this type of correlation by the American curves from Windsor, Vermont.

The original means of 11 trees are given in the upper line of figure 27. In the middle line these are smoothed by Hann's formula and in the lower line is the sunspot curve, displaced three years to the left in the portions since 1810 and one year in the same direction before that date. The tree crests anticipated the solar crests by three years when the trees were large and making good growth, but when small this anticipation of the sunspot maximum was considerably less. A correlation is evident, but it is hard to give a satisfactory explanation of the phase displacement. Figure 28 gives details of the time relation between tree-growth, rainfall, and solar activity. In figure 29 the curves of figure 28 have been summated on an 11.4-year period, as was done in figure 25. At the bottom is the sunspot curve from 1834 to 1912 inclusive; directly above it is the curve of rainfall for the vicinity of Windsor, compiled chiefly from records at Hanover and Concord and covering 1835 to 1912; above that is the tree-growth from 1834 to 1912, and in the upper line the sunspot curve is repeated with a displacement of −3 years.

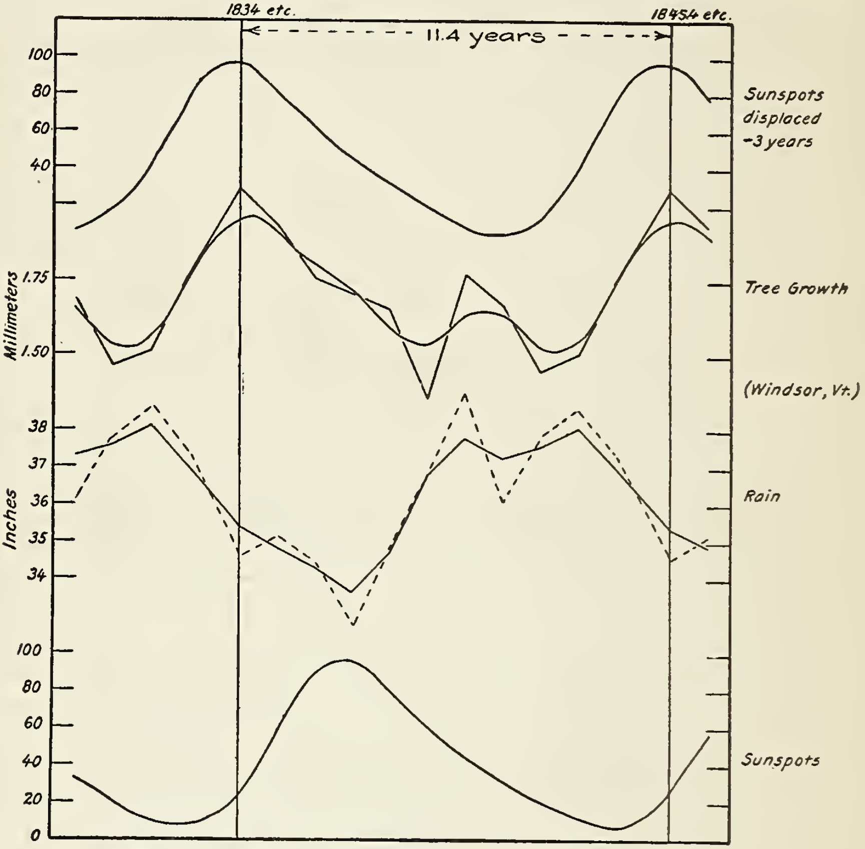


FIG. 29.—Correlation curves of solar cycle, rainfall, and tree-growth at Windsor, Vermont, 1835–1912.

THE SUNSPOTS AND THEIR POSSIBLE CAUSES.

If the sunspots are an index of some solar activity so far reaching as to affect our climate and vegetation, it is well to note very briefly their appearance and the suggested causes of their periodic character.

Appearance.—At first view sunspots are small black areas appearing from time to time on the sun. In actual size they vary from a few hundred miles in diameter to more than a hundred thousand. Rarely seen by the naked eye, the vast majority are only discovered through the telescope; hence it was only after the invention of that instrument that records of them were kept and their nature investigated. As Hale (1908) has found, they are cooling places; they merely look black by contrast with their more intensely bright background. His remarkable photographs show that they often have a rotation about their own center. They usually come in groups between latitude 5° and 25° in each hemisphere of the sun and are almost continuously changing in small details. Their life is usually less than one rotation of the sun.

Schwabe in 1851 announced their periodic character with maxima every 11 years. During sunspot maximum a small telescope will show 5 to 20 spots, but during the minimum one may search for weeks without finding a spot that can be certainly recognized. Records of the numbers of spots were specially collected by Wolf for many years and later by Wolfer of Zurich. At the present day many observatories are taking daily photographs of them. The term relative sunspot number was invented to convey an idea of the average number of spots visible at any one time under favorable circumstances. The number actually counted receives a simple correction for unfavorable weather or small telescope, so that the published numbers shall be as nearly standard as possible.

While the spot appears black and may possibly be sinking into the sun, it is usually attended by intensely bright areas or faculæ and even by prominences which are often violently explosive, ejecting matter hundreds of thousands of miles from the sun's surface. Thus the sunspot maximum indicates increased activity at the surface of the sun, which, according to Abbot (1913 and 1913^2), is actually sending us increased heat radiation. During the maximum the magnetic condition of the earth is profoundly affected, as evidenced by northern lights, magnetic storms, earth currents, and variations of the earth's magnetic constants. This relation to the earth's magnetism has been recognized from the first discovery of the periodicity of sunspots. But the effect of the change of solar radiation on climate and ordinary weather elements is more obscure. General effects on climatic conditions have been admitted as probable by Penck (1914), but in general the great weight of opinion has been against a traceable effect of solar activity on weather or climate.

From the description above it is easily seen that the sunspots are not likely to be in themselves the fundamental solar activity, but rather an index of something else, and possibly a very sensitive index, for the percentage change in spot numbers is hundreds of times as great as the percentage changes in measured radiation between sunspot maxima and minima.

Suggested causes of sunspots.—The cause of sunspots is still a matter of conjecture, and there is no generally accepted hypothesis to explain them. There is analogy to our clouds in that both indicate decreased temperature. In their limitation to certain latitudes they resemble the belts of Jupiter. The belts of Jupiter are roughly the lines of division between the powerful easterly equatorial current and the slower moving zones on either hand; and indeed this has been suggested as an explanation of the particular location in latitude of the sunspots, for there is an increase in speed of rotation of the sun's surface as the equator is approached. Their periodic character is very difficult to explain. Fundamental periodic changes in the body of the sun have been suggested and, in the absence of better explanations, some such statement hazily indicating the direction in which explanation is to be sought, is perhaps the best that we can do. Planetary influence, however, has often been proposed as the cause. The near agreement between the revolution period of Jupiter and the sunspot period has naturally attracted attention. Stratton (1911–1912) has made a very interesting study of the appearance, continuance, and disappearance of spots on portions of the sun facing toward or away from Jupiter and Venus. A few per cent more spots do originate and disappear on the "afternoon" of the side facing Venus than on other longitudes, but he considers the case of physical relationship not proven.

Planetary influence is sought in a theory proposed by W. J. Spillman (1915). In this theory gravitation is assumed to be due to pressure variations in the ether arising from electronic rotation in the attracting body. The varying speed of a planet in its orbit between perihelion and aphelion, involving varying quantities of energy, requires, he says, an interchange between the kinetic energy of the plant and the atomic energy of the central attracting body. This atomic energy is in the vibrations of the electrons, but he thinks it is likely to affect both the temperature and the electric activity of the central body. The effect in this way of Jupiter and Saturn would exceed the sum of all the other planets combined and is therefore the only one considered. The effect of Jupiter with its substantial variations in distance between perihelion and aphelion predominates, and we have a marked resemblance between the sunspot curves since 1770 and the differential planetary effect. One notices that this interchange of energy would presumably affect all parts of the sun alike and that therefore we could not expect an excess of sunspots on the side facing Jupiter.

H. H. Turner (1913; cf. Sampson, 1914) has worked out an hypothesis which is stimulating, even if not yet acceptable. He supposes that the Leonid swarm of meteors, revolving once in about 33 years in a very eccentric orbit, is at the basis of the sunspot recurrence. These meteors were observed in countless swarms, filling the sky for a few nights in November 1799, and again in 1833 and 1866. In 1899 they were expected, but failed to appear in large numbers, having probably been swerved to one side through the attraction of some planet. Turner finds that they have passed near Saturn several times in the last 2,000 years. At some of these encounters a quantity of meteors may have been detached and losing their own velocity may have fallen nearly straight toward the sun, grazing its outer surface in their circuit at a velocity of 400 miles per second, then swinging out to aphelion near their place of encounter, and completing their revolution in about 11 years. Successive returns of the main Leonid swarm, approaches of Saturn, and perhaps even the influence of other planets would be sufficient to perturb this meteoric swarm and cause the variations in period observed. On their terrific flight close to the sun many would be caught in the sun's outer atmosphere, thus in some way causing sunspots.

This hypothesis attempts to explain the period and its irregularities, including the double and triple period. I refer to it at some length because the investigation of trees gives evidence not only of climatic variations in the sunspot period, but of double and triple sunspot periods and possibly of still larger fluctuations. Turner's hypothesis warrants further discussion to explain why the spots appear in subtropical latitudes but not at the solar equator. In the planetesimal hypothesis of Chamberlin and Moulton, the rotation of the sun on its axis is attributed to the material falling back upon it after receiving a slight orbital motion from the visiting star. The authors state that the process may still be going on. This view is sustained by arguments based on the zodiacal light and on meteors, both of which seem best explained as planetesimal matter not yet returned to the solar mass. Matter as yet unabsorbed would very likely consist of particles which had been given just enough orbital motion to escape the surface of the sun on their periodic return. The particles for the most part would then have extremely eccentric orbits and pass close to the sun's surface at tremendous velocity. They would be moving largely in the plane of the solar system and consequently would pass close to the sun's equator. If finally caught in the sun's atmosphere, friction would reduce their motion, turning a large part of it into heat and a part into forward movement of the sun's atmosphere. Thus the planetesimal hypothesis explains the equatorial acceleration. A large meteoric group, as suggested by Turner, is therefore consistent with the hypothesis. The undefined zone between the accelerated equator and the slower-moving latitudes on each side would present much mechanical disturbance and favor the formation of local vortices. Such a process as this would be accompanied by the increased radiation in sunspot maximum which has been observed. If this hypothesis has a basis of fact, it is probable that the increased radiation at that time would come from the sun's equator, where there are no spots. Increased rotational movement of the equatorial zone at the sunspot maximum should be susceptible of observation by spectroscopic means. The meaning of the slow movement of this spot-forming zone toward the equator, as sunspot maximum changes to minimum, is not clear under this hypothesis; nor does one see why the secondary spot described by Hale (1919) should have its definite location following the principal spot, nor why the magnetic polarity of spots changed near the last sunspot minimum. These phenomena, recently observed by Hale and his collaborators, point toward causes within the sun.

Length of the sunspot period.—For many years Newcomb's figure of 11.13 years has been commonly quoted. However, recently some of the best authorities say frankly that it may be anywhere from 11 years to nearly 12 years. Schuster (1898–1906) discussed analytically the best known sunspot numbers, those since 1750. This has been followed by the work of Kimura (1913), and especially Turner (1913) and Michelson (1913). In general, the analyses by Schuster and Kimura, and by Turner in his earlier papers, produce a large number of possible periods of small amplitude. Michelson, however, goes to the other extreme. "Indeed," he says, "it would seem that with the exception of the 11-year period and possibly a very long period (of the order of 100 years) the many periods found by previous investigators are illusory." Turner in his hypothesis referred to above reduces the number to a few, which supply a basis for his reasoning. Michelson had favored a period of about 11.4 years and Turner says that only this 11.4-year period is sensible at the present time.

Tree-growth and solar activity.—The correlation shown in this chapter suggests a possible use of the annual rings of trees in the study of solar activity. There are two lines which such a study might take. An intensive line already mentioned includes the search for wet-climate trees showing the solar rhythm in their growth and the determination of the conditions under which they produce this curve. An extensive line of study is obviously possible also in reconstructing, as far as possible, a history of the sunspot cycle from very old trees. The yellow pines of Arizona give evidence that 500 years ago the cycle was operating very much as now. The sequoias, if correctly interpreted, already carry the history back over 3,000 years, and beyond that fossil trees may stretch the time covered in part at least into millions of years.

VII. METHODS OF PERIODIC ANALYSIS.

Need for such analysis.—During these modern times of rainfall and sunspot records we may compare such records with tree-growth and obtain the interesting correlations exhibited in the last two chapters; but the tree records extend centuries and even thousands of years back of the first systematic weather or sun records of any kind. Without being over-precise or exhaustive, it is interesting to note that California weather records began about 1851. Records on the Atlantic coast began largely in the half-century before that date. London has a rainfall record since 1726, Paris since 1690, and Padua since 1725. Good sunspot records began about 1750, but the number of maxima and minima is known between 1610 and 1750, although the exact dates are uncertain. All this does not carry us very far back, but it serves as an excellent basis for the correct interpretation of the record in the trees.

It would be possible to apply correlation formulas to the Arizona tree records and perhaps to the sequoias and construct a probable rainfall record for long periods of time, but apart from Huntington's study of the "Climatic Factor in History," the chief use of such a record would be in studying the laws which govern rainfall; and this is best done through cycles. We shall find that the sunspot cycle plays an important rôle in rainfall. But we find traces of the solar cycle in nearly all of our tree groups, and evidently the way to read the trees is to study first of all their alphabet of cycles. Hence the best methods of identifying cycles must be used.

Proportional dividers.—If a short series of observations is to be tested for a single period, it can be done by mathematics, but it will take many hours and give a result in terms so precise as often to deceive. This, for example, has been the difficulty with the mathematical solution of the sunspot curve. It seems to the writer that the safer way to solve such a curve is by a graphic process, plotting the curve and applying equal intervals along it. An extremely good instrument for this purpose is the multiple-point proportional dividers. By a system of pivots and bars, 16 or more points are maintained in a straight line and at equal intervals, while the space between two successive points may be drawn out from one-eighth inch to one inch. The remarkable persistence of the half sunspot period in the early Flagstaff trees was detected in this way.

The projection of equal spacing on curves as long as 12 to 15 feet has been done by a 10-foot india-rubber band with small metal clips pinched on at regular intervals. As the band was stretched all the intervals were enlarged by equal amounts, and periodic phenomena were detected. Similar use could be made of the sharp shadows cast by the glowing carbon of an arc-light. The shadow of a transparent scale could easily be cast in all sizes upon a plotted curve. But all these methods of equal spacing on a plotted curve leave far too much to the individual judgment of the investigator.

THE OPTICAL PERIODOGRAPH.

A method of periodic analysis well adapted to the work in hand has been developed by the writer as the need for it became more and more evident. Along with the feeling of need for rapid analysis was the increasing recognition of the desirability of some process which would place mere individual judgment and personal equation as far in the background as possible.

Schuster's periodogram.—In 1898, Schuster suggested the use of the word "periodogram" as analogous to the word spectrogram; that is, a periodogram is a curve or a photograph which indicates the intensity of time periods just as the spectrogram indicates intensity of space-periods or wave-lengths. The spectrogram commonly gives its intensities by varying photographic density along a band of progressive wave-lengths. For the periodogram Schuster made simply a plotted curve, of which the abscissæ represented progressive time-periods and the ordinates represented intensities. He made a mathematical analysis of the sunspot numbers and constructed a periodogram which is reproduced in figure 30. It shows periods at its crest at 4.38, 4.80, 8.36, 11.125, and 13.50 years.

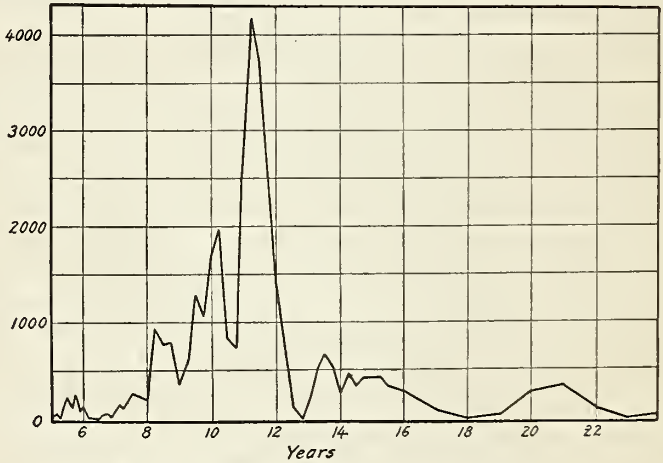


Fig. 30.—Schuster's periodogram of the sunspot numbers.

The optical periodogram.—It is, of course, not necessary that the periodogram should take the form of a plotted curve with intensities represented by ordinates, nor yet need it be exactly like a spectrogram showing intensities by density. The first periodogram produced by the writer is shown in plate 9, A. It is an analysis of the sunspot numbers from 1755 to 1911. The existence of a rhythm in any specified period is indicated by a beaded or corrugated effect. A line across the corrugations gives in fact the rhythmic vibrations of the cycle. On a moment's examination this periodogram shows much of the information which has been under discussion for many years. The 11-year period is the most pronounced, but it is not so superior to all others as would be expected. It may be of any duration from 11.0 to 11.8 years, but 11.4 is a good average. There is obviously a period somewhere between 9.5 and 10.5 years and one between 8.0 and 8.8, but it is less conspicuous. Faint indications of periods are found near 14 years. The double of 8.4 is seen between 16 and 17 years. The double of the 10-year period shows near the 20 and at 22 the double of the 11 begins.

The preliminary part of producing this periodogram is the construction of the "differential pattern" shown in plate 9, B. This pattern is the optical counterpart of a set of columns of numbers arranged for addition, as when one summates a series of annual measures on a 10-year period, for example. The series is arranged in order with the first 10 years in the first line, the second 10 in the second line, and so on. In the case of the pattern the lines are made indefinitely long, so that the optical addition may be done in other directions than merely straight downward, for by making the additions on a slant a different period comes under test.

In order to produce this pattern the sunspot curve was cut out in white paper and pasted in multiple on a black background. The left end of each of the upper lines is the date 1755. Each successive line is moved 10 years to the left, so that passing from above vertically downward each line represents a date 10 years later than its predecessor. This continues from 1755 to 1911, and the lower 10 lines show the latter date at their right ends. It is not necessary that any of the lines should be full length, as we use only a part of each. By passing the eye downward from the top, a period near 10 years will show itself at once by a succession of crests in vertical alinement. If the crests form a line at some angle to the vertical, then the period they indicate is not exactly 10 years. It is more if the slant is to the right and less if to the left. The horizontal lines are spaced the equivalent of 5 years. Hence, if we measure the angle made between a vertical line and a line joining two crests in successive horizontal lines, we may easily calculate by simple formulas the period indicated.

Since the photometric values of all the curves in the diagram are proportional to the plotted ordinates, the photographic summation of the whole pattern in a vertical direction is almost an exact analogue of a numerical summation. This summation is simply done by a positive cylindrical lens with vertical axis. This brings down on the plate a series of vertical lines or stripes. If, now, we cut across these lines with a horizontal slit, the light coming through this slit from one end to the other will be the summation of the diagram in the vertical.

But the photographic summation may be done at any slant instead of only in the vertical, and therefore the sensitive plate may be made to summate these curves through a long range of periods. In order to get a long range of periods, the diagram was mounted on an axis with clock-work and slowly rotated in front of a camera with a cylindrical lens for objective, a horizontal slit in the focal plane, and a sensitive plate passing slowly downward across the slit by clock mechanism. In this way a full range of possible periods come under the summing process, and when a real period is vertical the crests of the curves form vertical lines which come down as a series of dots or beads in the slit. When no period is in the vertical the light coming through the slit is uniform. Of course, there is a practical limit to the different angles at which the diagram may be viewed. An angle too far in one direction, making the tested period very small, would require a great number of duplications of the curve, while too great an angle the other way, making the tested period very large, catches the curve in the nonsymmetrical form and introduces errors. In the periodograms actually made of the sunspot curve the minimum period tested was 7 years and the maximum 24. One notes especially that this is a continuous process and that all periods from the minimum to the maximum are tested.

Application to length of sunspot period.—The interest in the sunspot period makes a special consideration of plate 9, C, worth while. This figure is a photograph of plate 9, B, taken out of focus for the purpose of calling attention to certain general features. In B the eye naturally turns to the sharp outlines and notes its minute details. In C the crests of B are changed into large blotches connecting somewhat with their nearest neighbors and varying in intensity. The alinement which they form in a nearly vertical direction is a graphic representation of the period. If the line were exactly vertical the period would be 10 years. The slant to the right shows more than 11. If the line were straight the period would be constant. It is evident that there are several irregularities in it. Having a number of exactly similar lines side by side, the irregularities are repeated in each and thus strike the consciousness with the effect of repeated blows. These irregularities are the discontinuities referred to by Turner in connection with his hypothesis. It is evident at a glance that the sunspot sequence divides itself into three parts, namely, a 9.3-year period, 1750–1790; then an interval of readjustment, 1800–1830, with a 13-year period; and lastly an 11.4-year period lasting to the present time (values approximate).[1] But the latter is not perfectly constant, for after 1870 there is a change in intensity. The breaks thus shown and Turner's dates of discontinuity are compared in table 6.

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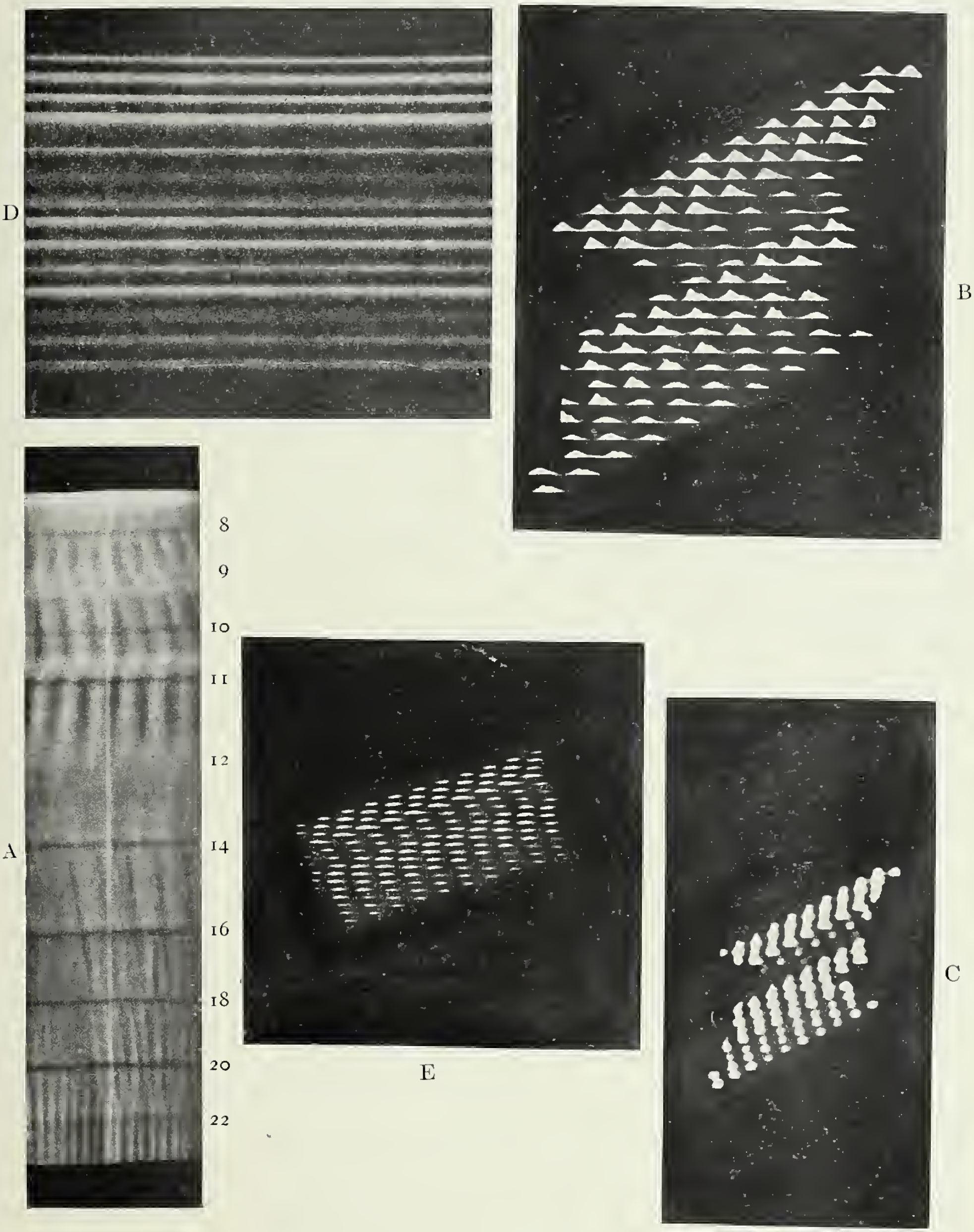
[1] In discussing the periodicities of sunspots (1906², pp. 75–78) Schuster divided his 150 years, from 1750 to 1900, into two nearly equal parts. He found in the first part two periods of 9.25 and 13.75 years acting successively, and in the second part, a period of 11.1 years.



- A. Periodogram of the sunspot numbers, 1755–1911. Corrugations show periods. The numbers give length of period in years. The white line is the year 1830 and shows phase.
- B. Differential pattern used in making the periodogram, consisting of the sunspot curve mounted in multiple.
- C. Same pattern photographed out of focus to show discontinuities in the vertical lines.
- D. Sweep of sunspot numbers, 1755–1911.
- E. Differential pattern of sunspot numbers made by the periodograph process.

By means of this diagram one can discover at a glance the origin of many of the periods which Michelson thought were illusory and in which opinion he was largely right. We can plainly see a 9.3-year period in the early part of the curve. Let us call this part of the sequence A_n and its broken continuation near the center B_n, and the lower and later part giving the 11.4-year period C_n. Thus we get at once three periods, 9.3, 11.4, and something over 13 years. If, now, we bring the average A_n into line with the average C_n as the periodograph does, we get 11.4 years. If we bring the average A_n into line with the C_{n-1}, we get close to 10 years. If we bring into line A_n and the heavier parts of C_{n-2}, we get 8.4 years or thereabouts. And at 5.6 years we find a period which is just half of C_n and at 4.7 the half of A_n, and so on. It is like a checker-board of trees in an orchard; they line up in many directions with attractive intensity. But plate 9, c, helps remove some of the complexity of the sunspot problem. It shows us that while these various periods are apparent, they are improbable and needless complications. The diagram supplies a basis for profitable judgment in the matter. Hence to avoid just such awkward cases as the sunspot curve, a differential pattern is considered to be a necessary accompaniment of the periodogram in doubtful cases.

Table 6.—*Discontinuities in the sunspot cycle.*

Periodogram.	Turner.
	1766
Between 1788 and 1804.	1796
Between 1830 and 1837.	1838
Between 1870 and 1884.	1868
	1895

Production of differential pattern.—The work described above, consisting particularly in the production of a periodogram from the differential pattern, was done at Harvard College Observatory in 1913. The next fundamental improvement in the apparatus was in 1914, and consisted in a method of producing the differential pattern without all the labor of cutting out the curves. It was simply the combination of a certain kind of focal image called a "sweep," and an analyzing plate. A single white or transparent curve on a black background is all that is now needed as a source of light. An image of this is formed by a positive cylindrical lens with vertical axis. In the focal plane image so produced each crest of the curve is represented by a vertical line or stripe and the whole collection of vertical lines looks as if it has been swept with a brush unevenly filled with paint and producing heavy and faint parallel lines. Each of these lines represents in its brightness the ordinate of the corresponding crest. The sweep of the sunspot numbers is shown in plate 9, d. Any straight line whatever in any direction across this sweep truly represents the original curve, not as a rising and falling line but in varying light-intensity. A plate with equally spaced parallel opaque lines, called the analyzer or analyzing plate, is placed in the plane of this sweep. These lines may be seen in plate 9, E. When the analyzer is turned at a small angle to the lines of the sweep, each transparent line shows the full curve or a substantial part of it in its varying light intensities. These numerous reproductions are all parallel to each other, separated by equal dark lines, and each one is displaced longitudinally with reference to its neighbors, thus presenting the characteristics of the differential pattern. By twisting the analyzer with reference to the sweep while the two remain in parallel planes, different periods may be tested; for as the analyzer twists, each reproduction varies in respect to its length and its displacement from its adjoining neighbors above and below. When a period is formed it shows itself, just as in the original differential pattern, by rows of dark and light spots in alinement more or less perpendicular to the analyzing lines, as in plate 9, E. These light and dark rows are analogous to interference fringes and are identical with the elaborate but provokingly useless designs on a wire screen in front of its reflection in a window, or with the parallel fringes when two sets of parallel lines are held at a slight inclination to each other.[1] Alinements are always best recognized by holding the paper edgewise and looking at the diagram at a low angle rather than in a perpendicular direction.

The analyzing plate resembles a coarse grating with equally spaced parallel lines. Much difficulty was experienced in making it. It is most satisfactory if made on glass with strong contrast between the opaque and transparent parts. The grating now in use was produced by photographing a 10-foot sheet of coordinate paper upon which 165 lines of black gummed paper had been carefully fastened. The coordinate lines permitted the spacing to be done with exactness. The width of the transparent space throughout was three-tenths of the distance from center to center. This was carefully photographed by a good lens at different distances. Glass prints were made from each negative and are still in use.[2]

Theory.—The formula for the period is very simple:

Let y = length of curve in years or other time-unit employed.
l = length of curve image across sweep lines in centimeter or other unit of length.
s = spacing center to center of analyzing lines in unit of length.

Then $\frac{l}{s}$ = number of analyzing lines in curve when lines are parallel to sweep.
$\frac{ys}{l}$ = number of years in 1 line when lines are parallel to sweep.

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[1] Roever (1914), has used somewhat similar interference patterns to illustrate very beautifully certain lines of force.

[2] A very superior analyzing plate has recently been made from a ruled screen such as is commonly employed in half-tone engraving.

Now, taking analyzing lines $\overline{aa^1}$ and $\overline{bb^1}$ in figure 31 as horizontal, and letting the sweep be inclined as a small angle δ with the analyzing lines, the number of lines required to cross the sweep in the direction *ab* perpendicular to analyzing lines will be increased and hence the value in years between two analyzing lines will be decreased; hence

$$\frac{ys}{l}\cos\delta = \text{years per line from } a \text{ to } b.$$

If the fringe is perpendicular to the analyzing lines, its period is the distance $\overline{ab}$ in years and we have for this special case:

$$p_1 = \frac{ys}{l}\cos\delta.$$

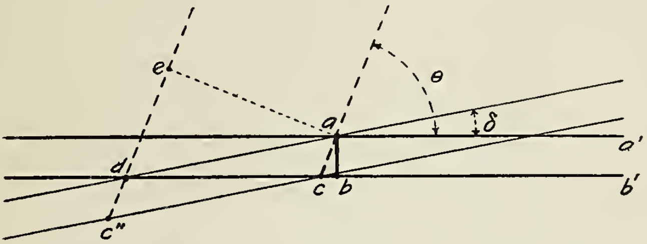


FIG. 31.—Diagram of theory of differential pattern in periodograph analysis.

If, however, the fringe takes some other slant, as the direction $\overline{ac}$, making the angle θ with the analyzing lines, then the period desired is the time in years between *a* and *c*. That equals the time between *a* and *b* less the time from *b* to *c*. Now $\overline{bc}$ in years would equal $\overline{ab}$ cot θ except for the fact that the horizontal scale along $\overline{bc}$ is greater than the vertical scale along $\overline{ab}$ in the ratio $\frac{\cos\delta}{\sin\delta}$ and therefore a definite space interval along it means fewer years in the ratio of $\frac{\sin\delta}{\cos\delta}$. Hence we have:

$$\overline{bc}\ (\text{in years}) = \overline{ab}\ (\text{in years})\tan\delta\cot\theta$$

or

$$P = p_1(1 - \tan\delta\cot\theta)$$

which is the period required.

The separation of the fringes needs to be known at times in order to find whether one or more actual cycles are appearing in the period under test. In figure 31

$$\overline{ab} = s \qquad \overline{ad} = \frac{s}{\sin\delta} \qquad \overline{ae} = \frac{s\sin(\theta-\delta)}{\sin\delta}$$

which is the width required.

THE AUTOMATIC OPTICAL PERIODOGRAPH.

The present apparatus combines the two processes whose development has been described above. The second process developed is really the first one in the present instrument.

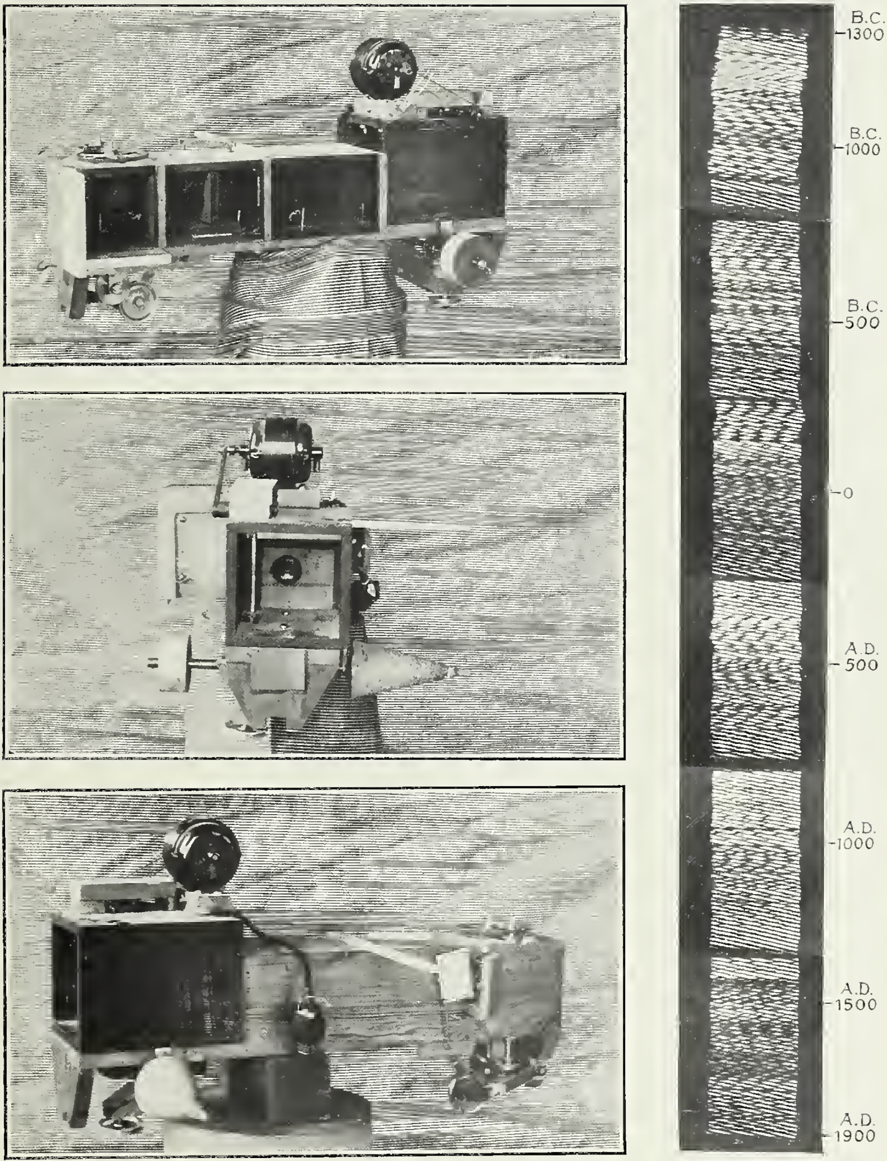
The curve.—The curve is prepared by cutting it out in a thick coordinate paper. The space between the curved line and the base is entirely removed and the curve becomes represented by area. In order to make the density still greater, the paper is painted with an opaque paint so that the brilliant light passing through will come through only the curve itself and not the paper. A special window-shutter is made to occupy the lower 2 feet of the window, whose width is some 50 inches. The curtain can be drawn down to the top of this, excluding the light around the edges. This window-shutter has a door in the upper part to give access to the interior. Within this box is a sloping platform upon which a mirror 8 by 46 inches is placed. This mirror is about 35° from the horizontal position and when looked at from a horizontal direction it reflects the sky from near the zenith. On the side of this box toward the room is a slit 45 by 3 inches in size. This extends horizontally and is on a level with the mirror. Below this slit is a narrow groove for taking the lower edge of the curve paper and above this slit is a strip of wood on hinges, so that when the lower edge of the curve is placed in the narrow groove below, this hinged strip closes down on the top and holds the curve in place directly in front of the mirror. Looked at from a horizontal direction within the room, the curve is seen brightly illuminated by light from the sky not far from overhead.

Track and moving mechanism.—About 7 feet from the curve the track begins and extends back 45 feet in a perpendicular direction. The track consists of 3 rails. The center rail is of uniform height and takes the single rear wheel, whose motion controls the movement of the film at the back of the camera. The right-hand rail is also uniform in height and supports one of the front wheels. The left rail is variable in height and supports the driving-cone, which serves as the other front wheel. The cone is 6 inches long and 3 inches in greatest diameter. It rests on a side rail whose elevation and distance from the center can be altered. The purpose of this particular mechanism is to vary the speed with which the camera travels along the track, for the time of exposure is approximately proportional to the square of the distance from the curve, and therefore when the camera travels from the near position to the far position it must slow down in rate as it goes along. The left rail, therefore, at the near position is close to the center and low down; in the middle and outer parts of the track it gets farther away and higher up, since the parts of the cone near the vertex travel on it. The axis of the cone carries a bevel gear meshing with another bevel attached to a vertical axis with a worm gear at the top, which the electric motor drives with a belt connection. In order to aid the motion of the camera, a cord passes from its back to the outer end of the track and by a system of pulleys and weights exerts a slight constant force. The motor is so connected that the camera travels away from the curve. The details here described may be seen in plate 10.

The differential pattern mechanism.—The camera is divided into three separate compartments, to each of which access is obtained by a sliding door moving in grooves on the side. The front compartment produces the differential pattern. It is about 7 inches long by 5 inches wide in the clear and 4 inches high. It is nearly divided into two parts by a partition which comes down from the top at about 2 inches from the front end. This partition does not go down to the floor of the compartment, but leaves a space of about an inch. A hole 1.5 inches in diameter is cut through the front of this compartment a little above its center, and another hole of the same size to match is cut through this partition, while at the back of this compartment a large opening is made a little over 2.5 inches wide and about 2 inches high. The lens is carried on a special carriage consisting of a horizontal and a vertical part. The vertical piece has a hole 1.5 inches in diameter cut in it, and the lens is mounted over the hole. The lens now in use consists of a spherical lens concavo-convex 2 inches in diameter and 12 inches in focus placed on the inside, and a positive cylindrical lens of the same size and focus placed on the outside with axis vertical. The convex side of each lens is placed outward. The lens carriage is placed partly under the partial partition and the lens in its holder comes directly between the two holes mentioned. When the sliding door of the compartment is down, the compartment is sufficiently light-tight to fulfill all the requirements of a camera. The movable carriage of the lens is mounted on two small glass tubes and runs between guides. A spring at its back end pulls it toward the position of focus for distant objects, where its motion is stopped by a pin. A long screw is passed through a hole in the bottom of the camera box and enters the bottom of this lens carriage, so that an automatic arrangement outside and underneath the camera can regulate the focus. This consists of a vertical axis with two lever arms. The upper lever arm is a short one connected to the screw which comes from the lens board. The lower lever arm is some 4 inches below the upper and goes off in a direction nearly at right angles; it carries on its end a wheel in a horizontal position. This wheel is so placed that it runs on an especially arranged track attached to the side of the center rail of the main track. By varying the elevation of this special focussing track in different parts of the main track, the focus of the lens can be automatically controlled.

At the back of this first compartment is the analyzing plate, the same plate used in previous work. The spacing of its lines is 0.5 mm. from center to center. The proportionate transparent part is about three-tenths of the center-to-center measurement. The area covered by these lines is 1 by 3 inches, making about 156 lines. The photograph is transparent with dense black lines in it. The glass has been cut down to a convenient size, and this plate is mounted at the back of the first compartment with the film side of the plate toward the back. This plate is over the large opening at the back of the first compartment. The differential pattern is formed automatically by the lens on this plate. The plate is held in a fixed position with its lines nearly vertical but inclined about 12° to the lines of the sweep formed by the lens. This produces fringes more or less horizontal in direction. Varying periods are tested by changing the distance from the curve which alters the scale of the sweep while the analyzing lines are unchanged. As the scale of the sweep changes, the fringes appear to rotate about the center of the differential pattern. Immediately behind the analyzing plate are two condensing lenses described in the next topic. They bring the general beam of light to a focus about 6 inches back of the plate. For visual work a movable mirror, just back of the plate, reflects the beam outside the camera box, through an eyepiece to the eye. For photographic work a small total-reflection prism and simple lens are inserted about 5 inches back of the analyzing plate. These throw the beam outside into a special camera attachment in which ordinary films or plates may be used.

The periodogram mechanism.—The remainder of the camera is especially for the purpose of producing the periodogram from the differential pattern. Almost in contact with the analyzing plate is a condensing lens consisting of two cylindrical lenses about 2 inches in diameter and 6 inches focus; these are mounted with vertical axes and with their convex sides toward each other. The aperture of the condenser is about 0.75 inch in vertical height and 1.75 inches in length. The purpose of these condensers is to coverge the light which comes through the analyzing plate on the slit at the back. The second compartment is nearly the same size as the first, namely, about 6.5 inches long. At its front end is the analyzing plate with the condensers and at its back in the same optical axis is a vertical slit about 1 inch long and 1 mm. wide. The sides of this slit are beveled so that the slit itself is at the back. In the middle of this compartment is a powerful cylindrical lens or combination of lenses with horizontal axis. This lens is made up of 4 separate positive cylindrical lenses, each 2 inches in diameter and 6 inches focus. These all have their convex sides toward the common center. They are mounted on a movable carriage of wood which slips in place or may be removed entirely. The aperture of this lens system is about 1.5 inches long by 0.75 inch high. The effect of the condensing lens and of this cylindrical lens is to cast in the plane of the slit an area of light whose size is essentially a repro-



A. B.

A. The automatic optical periodograph.
B. Differential patterns of Sequoia record, 3200 years at 11.4.

duction of the aperture of the objective, namely, 1 inch high by 0.25 inch wide, but the detail in this area of light is brought in focus by the cylindrical lens and integrates the horizontal lines of the differential pattern. When, therefore, the differential pattern shows a series of horizontal fringes, they become reproduced by a series of horizontal lines crossing the slit, while in the slit itself they appear as a series of dots. When a period is disclosed by proper position of the camera, it will produce horizontal lines on the analyzing plate. A series of black and white dots, therefore, go through the slit into the final compartment; but when the distance is such that the lines on the differential pattern are at some slant, then, the integration carried into the slit being still horizontal, the illumination in the slit is uniform. In this way the beaded or corrugated effect in the slit indicates a period at that particular distance from the curve.

In order to read off periods directly in the final result without the necessity of making exact measures, an automatic signal or period indicator is introduced in this second compartment. Above the upper and lower ends of the slit are placed small pieces of mirror at 45°, and corresponding to these there are two small holes 0.25 inch in diameter in the side of the box. Outside of these holes again is a mirror at 45° reflecting light from the curve in the window. So long as the holes are open, direct light from the curve is reflected by the two sets of mirrors through the slit on to the film beyond, as will be described. A shutter is placed over the outer holes in the box with a lever carried down to the vicinity of the central rail. On the end of the lever arm is a wheel. At proper intervals small pieces of wood are placed in the side of the track, so that as the wheel passes over them the shutter is opened and light passes to the mirrors and makes a dot or a line on each side of the film in the third compartment. In this way marks can be placed on the film independent of the periodogram, and yet they can be spaced exactly to represent the different periods tested. Special periods, for example 5 or 10 years, etc., are indicated by the extra length and density of the marks produced. These appear on the margins of the periodograms in plate 11.

The final compartment at the rear contains a drum on a vertical axis which is slowly rotated as the whole mechanism moves along the track. The rear wheel resting on the center rail is connected by gearing to the drum, so that 1 mm. on the drum represents 42.7 mm. or 1.7 inches on the track. This makes a convenient length for the final periodogram. The drum can be detached, carried to a dark room to have a film pinned to its periphery, returned in a special light-tight box, and mounted on its axis for an exposure. The times of exposure depend on characteristics of the curve under test, but it is necessary to allow about 35 minutes for the range from 4 to 15 years, and several times that for the range from 15 to 25 years. Plates 10, 11, and 12 illustrate the apparatus and the periodic analysis produced.

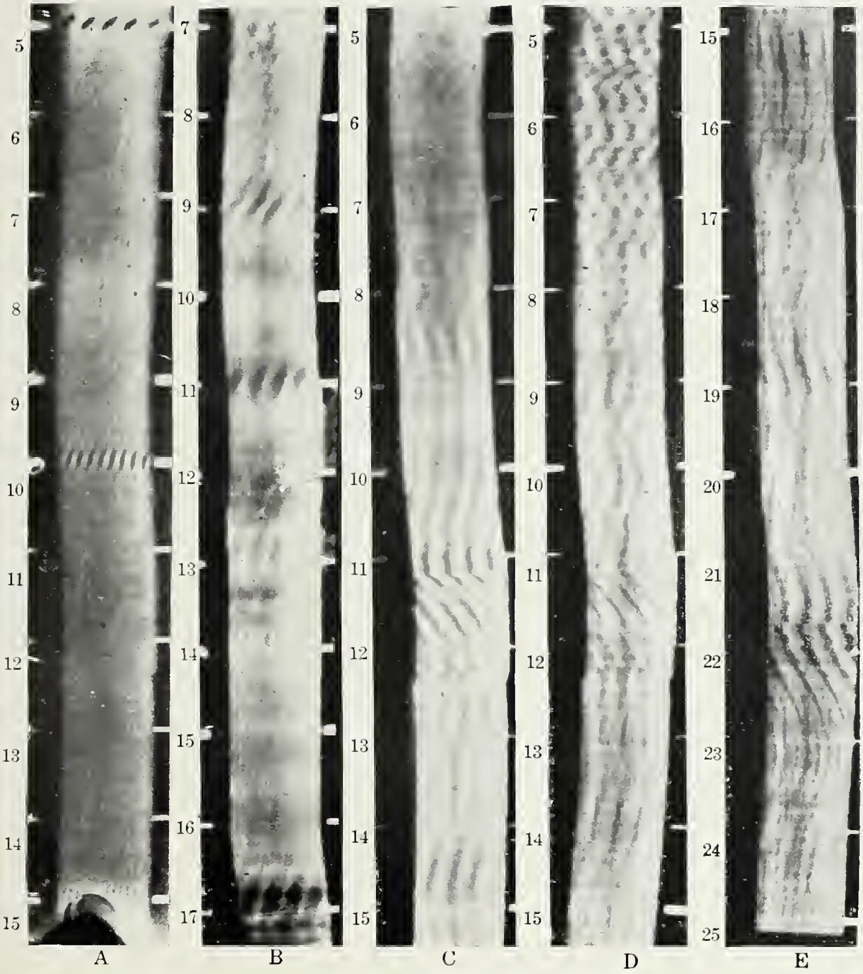
Periodograms.—Plate 11, which has been arranged to illustrate the work of the periodograph, shows several of the early periodograms which are comparatively free from obvious instrumental defects. In each the range of periods is marked on the left margin. Periods are indicated by the vertical band or ribbon breaking up into a series of horizontal dots or beads. For example, plate 11, A, is a periodogram of the 5-year standard period made for the purpose of calibrating the work of the periodograph. The 5-year period is very prominent near the top of the diagram in the plate. At 10 years its first harmonic appears with double crest, showing still that it is a 5-year period. At 15 years the second harmonic shows with a triple crest, and at 7.5 years the 3/2 overtone is evident with 3/2 crests. These overtones are always readily distinguished from the fundamental on the differential pattern. The differential pattern of this 5-year standard is shown in plate 12, Q. The instrument is set for analysis at 5.0 years. In this position the integrating lens sums up the rows of light crests as a series of dots on the periodogram.

Plate 11, B, is the analysis of a mixed standard used for calibrating the instrument. The curve contains sharp triangular crests at intervals representing periods of 7, 9, 11, 13, and 17 years, all mixed together and no two starting intentionally from the same point. These are all separated in the periodogram and the overtones of some may be seen. Such overtones can be distinguished from the fundamental on the differential pattern.

Plate 11, C, gives a periodogram of the sunspot numbers from 1610 to 1910, using before 1750 the probable times of maxima suggested by Wolfer. The best period is at 11.1 as usually quoted. If the variation from 1750 only is taken, the best period comes at 11.4. This periodogram shows a period at about 8.6. The degree of accuracy with which one can pick out the periodic point is a real criterion of the accuracy of the result selected. The differential pattern of this same series of sunspot numbers will be found in plate 12, A, in which the vertical rows of crests are readily distinguished. The sudden change in direction of the lines a little below the center of this and the two following periodograms is an instrumental defect due to slight unevenness in the track and therefore is without significance.

Plate 11, D and E, give an analysis of the Arizona 500-year record. The chief points of interest are the well-defined double-crested 11.6-year period and the 19-year and 22-year periods. Other weaker periods may be seen from place to place.

Resolving power of the periodograph.—The accuracy with which a period can be determined by the periodograph may be readily observed in the differential pattern and the periodogram. The pattern indicates a period by showing a row of light spots or crests in line. The accuracy



A. Periodogram of standard 5–year period.
B. Periodogram of mixed periods.
C. Periodogram of sunspot numbers, 1610–1910.
D. Periodogram of Flagstaff 500-year record, to show cycles between 4 and 15 years of length.
E. Periodogram of same continued to 25 years.

of the period is the accuracy with which the direction of this line can be ascertained. This depends on the length of the row of crests, on the shortness of each crest, and on their individual regularity or alinement. These characteristics may be noted in the plates and especially in plate 12, Q. Expressed in other terms, these resolving features are respectively as follows: (1) Number of cycles covered by the given curve. (2) Shortness of maxima in relation to length of cycle; if the maximum is sudden and sharp, as in rainfall, the accuracy may be very great; if the maximum is long, as in a sine curve, the accuracy is less. (3) Regularity in the maxima and freedom from interference. These features all appear in the differential pattern and hence the accuracy of any period is its most evident feature and all observers can judge it equally well. It is exactly analogous to the accuracy of a straight line passed through a series of plotted points which theoretically ought to form a straight line but which do not do so exactly.

The most important part of the constructed instrument which may alter the accuracy of analysis is the analyzing plate. The accurate spacing and parallelism of the lines is a mechanical feature and can be produced with care and attention to details, but the relation of width of transparent line to center-to-center spacing of the lines is a matter of judgment and the necessities of photography. As this relative width increases, the length of each crest in the pattern becomes longer and the row of crests becomes wider and less definite in direction. If the maxima in the curve under test are of the sine-curve type this relation is less important, for the light crests in the pattern will be long in any case, but for sharp, isolated maxima resolution is lost if the width of the transparent line is too great. In the instrument now constructed the ratio of transparent line to center-to-center spacing is 3:10, but a smaller ratio such as 1:10 could advantageously be used in certain cases if there is sufficient light to make photography easy.

The accuracy in reading a periodogram is at once apparent on its face. When the number of cycles is great as in plate 11, A, the rhythmic or beaded effect is short and very limited in extent, as in the 5-year period there indicated, and the period is accurately told. But if the number of cycles is reduced (as in plate 11, B or C) the periodic effect in the photograph extends over a greater range and its center can not be told with the same precision. The accuracy of estimation in the periodogram is therefore the actual accuracy of the result.

VIII. CYCLES.

Significance of cycles.—It has already been stated that three characteristics were observed in the curves of tree-growth: (1) correlation with rainfall; (2) correlation with sunspots; (3) general periodic variation. In the first and second of these the trees are compared directly with existing records, but in the third the tree record is available over hundreds and even thousands of years during which no human observations were recorded. Thus, if previous inferences are correct, the trees may reasonably be expected to give us some knowledge of prehistoric conditions. In the first attempt to secure such knowledge, the method which promises the most certain results is the analysis of ring variations in terms of cycles.

Correlatively, the study of cycles is of special value in climatic investigations. Such studies are undertaken for the purpose of predicting the future. The basis of daily or short-distance prediction is found in the conditions existing about the country at a given moment and a knowledge of the usual movement of storm areas. A basis for long-distance prediction is now generally sought in climatic cycles. Such cycles may or may not be permanent. Perhaps they are nothing more enduring than a series of wave systems on a water surface. Yet for the navigator a knowledge of the existing system is important, and so for the purpose of weather prediction we need to know the nature of the pulsations actually operating, and each one should be studied minutely. For this purpose the very long tree records and their presumably fair accuracy seem especially advantageous, since they give us a range in centuries which the meteorological records, with few exceptions, give only in decades.

A special and rapid method of carrying on the study of cycles has been developed in the periodograph which has been used in checking fully all the results in the present chapter. But after its recent completion and trial the fact became clear to the writer that its real service will be in a complete and thorough examination of all curves obtained, in order to derive a quantitative statement of the extension in time and space shown by each cycle. This in itself is a long process. Moreover, preliminary analysis of many tree curves reveals a very complex system of short-period variations in the trees, some of evident significance and some of little-known value as yet. The study of this complex of short periods together with other problems naturally suggested in the course of the work is reserved for the future; we shall now touch upon a few of the most important results reached in the analyses already accomplished.

Predominant cycles.—With the understanding that the study of cycles is not yet complete, it may be stated at once that the more conspicuous and general cycles at once apparent in the trees are directly related to the solar period. They are as follows:

5 to 6	years	approximate	half	sunspot	period.
10 to 13	“	“	full	“	“
21 to 24	“	“	double	“	“
32 to 35	“	“	triple	“	“
100 to 105	“	“	triple-triple	“	“

There are few if any periods over 20 years not in this list, but under 20 years several are fairly persistent, such as 19-, 14-, 10-, and 7-year periods. There is also a period of about 2 years which causes a frequent alternation of size in successive rings, giving a "see-saw" or "zig-zag" effect in the appearance of the curve. The discussion in this chapter, however, will be confined to the solar group of periods above listed and to a preliminary statement regarding the 2-year period. As the larger of these solar periods are very nearly simple multiples of the 11-year period, it is naturally suspected that they are or should be real multiples of the sunspot period. Hence I feel at liberty to speak of the "double sunspot period" or the "triple sunspot period" without committing myself to its exact length.

Locality and solar cycles.—Compared to the multitudes of meteorological districts about the world, the few isolated localities which have here been investigated seem very insignificant. The wet-climate trees near the Baltic Sea show variations following almost perfectly the curve of sunspot numbers. The Scotch pines just south of the sea have had good care since they were planted about 90 years ago. This care has prevented the excessive competition between individuals which characterize natural forests, and perhaps for that reason they give this remarkable record of external conditions. The trees to the north of the Baltic include spruces as well as Scotch pines, and show the same reaction. Both these groups are in comparatively level country and far from mountains. The group of pines from the Swedish province of Dalarne show the 11-year period somewhat less clearly. They were nearer the backbone of mountains which extends down the Scandinavian peninsula. The older trees of this group show evidence of a triple sunspot period. The groups growing in the mountains and in the inner fjords of Norway show extensive variations and even reversals. Some of the individual trees exhibit the sunspot period very well, while some show it inverted and some divide it into two crests. The older trees show evidence of an inverted double period.

The trees near sea-level, both at Christiania and on the outer coast of Norway, return again to the 11-year period. The former do not cross-identify well and the latter show occasional variations, such as double-crested period, inversion, etc. Variations of this kind were noted in different radii of the same tree. The trees from the south of

England show slight relation to the solar cycle. They show more prominently other variations, which, taken between 1870 and 1900, may have given rise to Lockyer's 3.8-year period (1905, 1906). The full tree record becomes more accordant on a 3.5-year period. In this group there appears to be a slight relation to London rainfall of a direct character, that is, the growth is larger with increased rain. Naturally in such a well-cultivated region there may have been large differences due to treatment of the soil, drainage, and so forth. The other two European groups, one from Pilsen in Bohemia and one from the north slopes of the Alps in southern Bavaria, do not show consistent agreement with the solar variation. Yet the former shows a double sunspot period which is illustrated below.

Coming to the American continent, the Vermont group may also be considered as growing in a wet climate. It shows a very strong single-creasted solar period, but the maxima come 3 years early during the last century. During the preceding century, when the trees were younger, the tree maximum is only 1 year early. The rainfall in this region shows the solar period also, but it is roughly inverted with respect to the tree curve. The Oregon group must be considered as in the wet climate of the temperate zone. It is near the Pacific coast and has abundant rain or snow. The solar cycle is probably in it, but it is not so conspicuous as other short cycles. When these trees are summed up on the 11-year period, they show about 10 per cent total variation with maximum and minimum coinciding with the Vermont group and therefore anticipating the sunspot maximum by 3 years.

The sequoias grow farther south and experience the heavy precipitation of the temperate-zone winter combined with dry-climate summer conditions—that is, the summers are mostly clear, but have occasional sharp local showers, often with lightning The tree-growth shows a relation to the rainfall in the great valley below and therefore we could expect some similarity to the Arizona pines. This does exist, but the exact 11.4-year cycle shown in the pines is less evident in the sequoias, though unmistakably there. The analysis of the long sequoia record will be shown below. In it several cycles between 7 and 15 years predominate in places. The 11-year period is plainly evident through most of the record and for some centuries is the predominant cycle, but for long periods other slightly differing cycles, such as 10 years, 12.6 years, or 13 years, are more evident. It is as yet impossible to say whether at these times there was a real change in the sunspot period, whether some subordinate period is operating in the sun, or whether only local conditions of some kind are the controlling factor.

The yellow pines of northern Arizona are dry-climate trees. They have a modified winter precipitation of the temperate zone. Spring and autumn have the complete dryness of the "horse latitudes," and the summers have the characteristic subtropical torrential thunderstorms. Rain is the controlling factor in these trees. The trees show a double-crested 11.4-year period through nearly all the 500 years of their record. This will be illustrated below. A 7-year period is also frequently observed, and the combination of the 7-year and 11-year periods may be the cause of these trees showing the double sunspot period prominently through most of their record by interfering to suppress alternate 11-year maxima. A triple sunspot period is very evident in the last 200 years, but is practically lost in the preceding 300. The pines and sequoias agree in showing a long period of about 100 years. The record of the pines is not long enough to give it much precision, and 120 years fits it more nearly. The 3,200 years of the sequoias analyze best at 101 years.

Illustrations of cycles.—Two methods of illustrating cycles in the tree curves are used here. One is the usual method of showing the plotted curves together with another curve indicating the cycle, so that agreements and disagreements may be noted. To this method also belongs the integrated or summated curve, which shows the mean variation in the desired period. The other method is by aid of various periodograph diagrams. These diagrams may similarly be divided into the differential pattern, in which variations from the cycle at any time may be noted, and the periodogram proper, which gives roughly the mean form of the cycles in a considerable range of periods. This form of presentation, being new and yet carrying more information than the former, will be given with some explanation after the curves themselves have been shown.

The 11-year cycle.—Only two tree records, the yellow pine and the sequoia, extend back of the first telescopic observations of sunspots. It is of peculiar interest to see whether the trees which carry the rainfall record back so far with a comparatively high degree of accuracy show the same cycle. In nearly all parts of the yellow-pine curve there are suggestions of an 11-year cycle. By tracing this throughout the record, the period is found to have a length of about 11.4 years, which is sufficiently close to the length of the sunspot cycle to be considered identical with it. This exact figure is not yet considered final, as future intensive study of the short-period variations in the trees may throw more light upon it. Taking 11.4 years as the probable length, the average total variation is found to be some 16 per cent of the mean growth. The period is generally double-crested with two well-developed maxima and minima, but they are rarely symmetrical. During the 120 years from 1410 to 1530 it shows most remarkable regularity. This feature, which was observed as soon as the smoothed curve was examined, is shown in figure 32. The tree curve in this diagram has been reduced to departures from its own mean and smoothed by Hann's formula. The short period is immediately evident, even without the 5.7-year cycle plotted below. This bit of record in the yellow pines and the 90 years of record in the wet-climate Scotch pines near the Baltic Sea give the finest examples of rhythmic growth yet found in the trees.

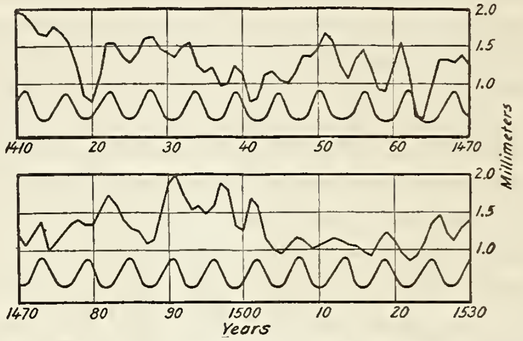


Fig. 32.—Smoothed curve of Arizona pines showing the half-sunspot period for 120 years.

In order to test for possible variations in the sunspot curve during these 500 years, the tree record from 1420 to 1909 has been divided into 8 periods of approximately 60 years each and the form of the 11-year period obtained in each. This is shown in figure 33. From this it appears that the 11-year cycle is not uniform throughout the whole 490 years covered by the curve. In general the cycle shows 2 maxima and 2 minima. From 1420 to 1660 the second minimum is generally the deeper. For the next 60 years the curve flattens out in a striking manner. From 1730 to 1790 the curve again shows variations, but they are not well related to this cycle. After 1790 there are again 2 minima, but on the whole the first is more conspicuous.

The 11-year cycle in sequoia.—The question of agreement between the sequoia and the yellow pine is a vital one. Although the sequoias grow in a locality some 450 miles distant, there is a similarity in the rainfall of the two places. Some attempt has been made to cross-identify the rings in the two groups, and the puzzling fact was revealed that from 1400 to about 1580 no certain identity could be found, though after that date it was evident in many places. The difficulty has been partly removed by applying this same method of analysis to the last 500 years of the sequoia. The result is shown in the dotted lines of figure 33. It is evident that from 1420 to 1476 the second maximum of the pines is almost entirely lacking in the sequoias. The same is true of the interval from 1602 to 1658. The sequoias show strikingly the flattening of the curve from 1670 or 1680 to 1727. In the remainder of the curves the sequoias show better rhythm in the sunspot cycle than do the pines.

Taking the evidence as a whole, it seems likely that the sunspot cycle has been operating since 1400 A. D., with some possible interference for a considerable interval about the end of the seventeenth century.

Correlation curves.—Figure 34 is arranged to show certain relations of special interest in this connection. At the top was found the mean pine and sequoia curves for 490 years averaged on an 11.4-year period. Below these the mean 11.4-year period for the last 60-year interval is given for each tree. This is required for proper comparison with the short interval of climatic records. Next the rainfall and temperature observed on the southern California coast are plotted, and last of all the inverted sunspot curve for a corresponding period. There appears to be a marked relationship between these curves. Even the subordinate crest, which sometimes shows in the change from maximum to minimum of sunspots, matches the suppressed second crest of temperature and the full second crest of rainfall and tree-growth. This would seem impossible in the absence of a physical relation between them.

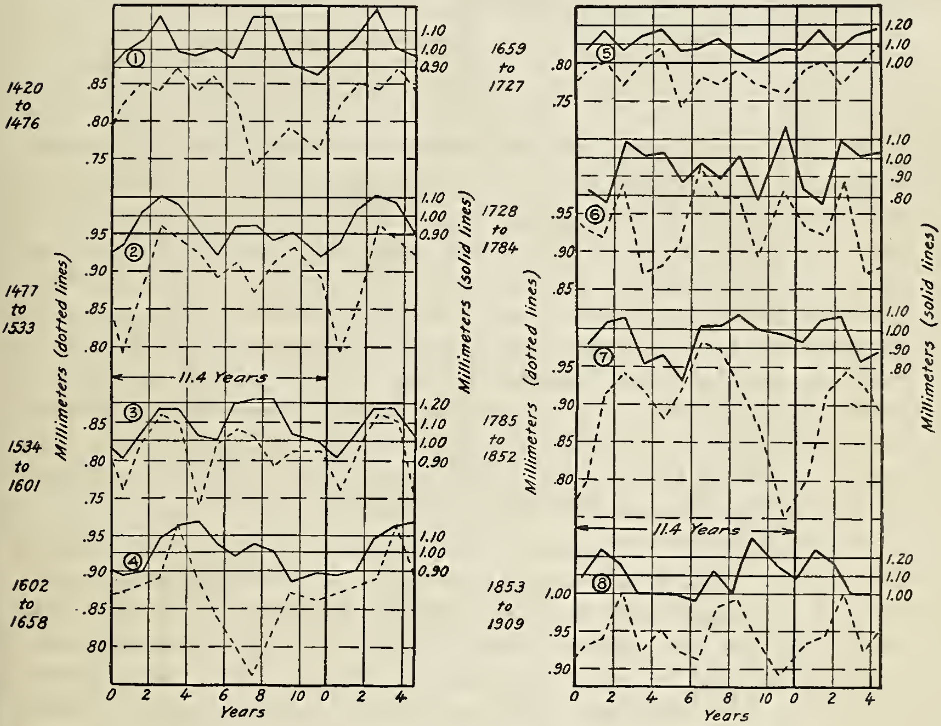


FIG. 33.—Changes in the 11-year period in 500 years. Solid line, Arizona pine; dotted line, sequoia.[1]

Double and triple cycles.—The first tabulation of the Arizona pines covered a period of only 200 years and included 25 trees. There were a few errors of identification in some of these trees, sufficient to flatten the curve a little but not enough to change the pronounced fluctuations amply shown in recent analysis. This 200-year record showed a very clear combination of the double and triple sun-spot periods. This was illustrated at the time in a drawing which is largely reproduced in figure 35. Curve No. 1 is a triple solar cycle 32.8 years in length; No. 2 is a double cycle 21.2 years long, and the third curve is a simple combination of the two. The fourth curve is the tree-growth, showing fluctuations which admirably combine these two periods. All subsequent analysis of these trees has entirely supported this result, as shown in the periodograph work below. When the length of curve was extended from 200 years to 500 years, the double solar period was found to prevail through almost the entire length, but the triple period does not appear to have affected the tree-growth in the earlier 300 years.

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[1] The correction for the ring 1580 was made too late for insertion in this figure. The two dotted curves between 1420 and 1533, therefore, should be moved one year to the left, while the third dotted curve between 1534 and 1601 becomes slightly modified. A slight change in the first Arizona curve is required by a correction at 1463 A. D.

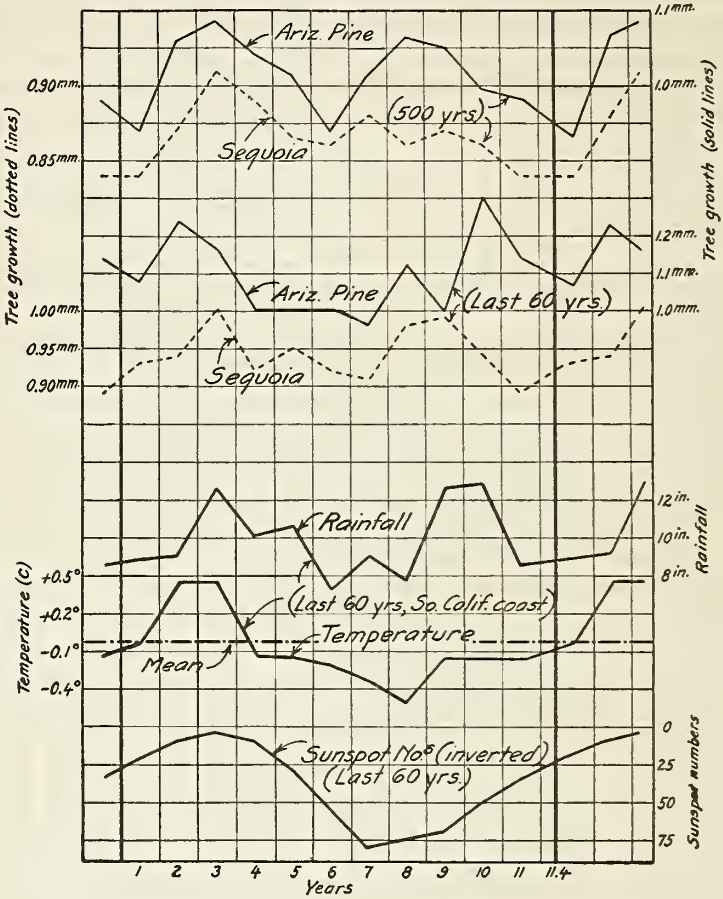

FIG. 34.—Correlation curves in the 11-year cycle.

Two other plain examples of the double solar type are illustrated in figures 36 and 37. The former gives the double cycle shown in a scattered group of trees of considerable age from the inner fjords and mountains of Norway. The earlier half of the curve includes 6 trees and the later half 8. The cycle beneath makes evident a well-developed rhythm in these trees. Figure 37 shows a very regular double sun-spot rhythm in the sequoias. There are many similar rhythms apparent in the sequoias, but as yet little study has been made of them. This one shows 80 years of the section D–12, whose identification was for a long time uncertain on account of its complacent character and badly compressed rings. The rhythmic character is so evident that no cycle needs to be placed below the curve. The period is estimated at 20 to 22 years.

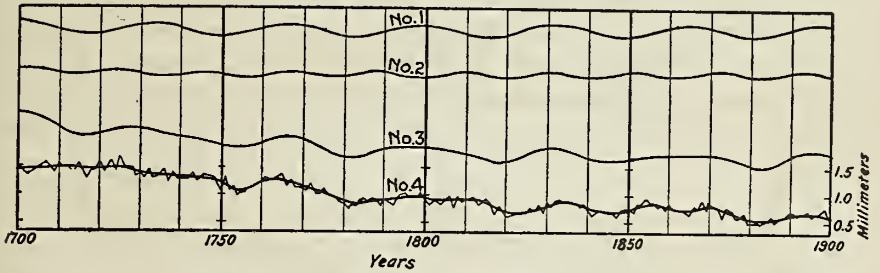

Fig. 35.—Early curve of Arizona pines from 1700 to 1900 A. D. (No. 4), compared with double and triple sunspot cycles combined (No. 3).

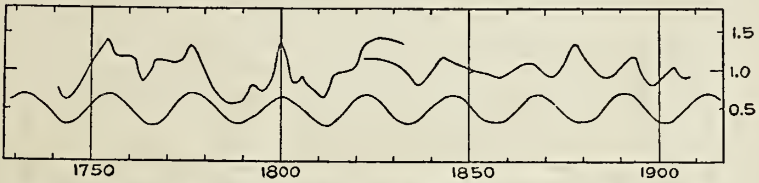

Fig. 36.—Double sunspot period in tree-growth at inner fjords of Norway; lower curve a 22.8 year cycle.

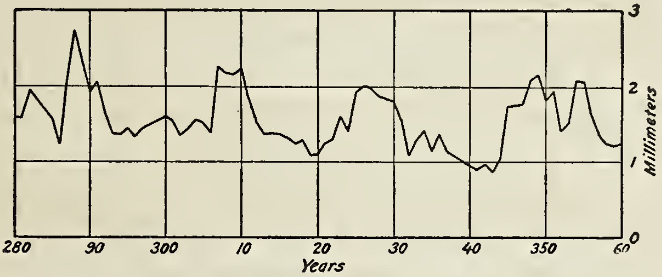

Fig. 37.—Double sunspot rhythm in sequoia, D–12 about 300 A. D. (Material obtained in 1919 shows the dates in this figure to be too large by 27 years.)

A triple solar cycle is shown in figure 38, giving the condensed curve of a single 400-year-old Norwegian tree. The upper curve gives the mean growth, and the lower curve is a simple 34-year cycle. The rhythmic character of the growth was clearly seen in the measures immediately after their completion, and the period at once suggested the Brückner cycle of 35 years. This interesting tree has been mentioned on pages 34 and 41.

A 2-year cycle.—In the cross-identification of the trees used in this investigation, a constantly recurring feature has been a marked alternation in size of successive rings, giving them an appearance of being arranged in pairs. In the plotted curves this produces a zig-zag or see-saw effect. Usually such effect lasts a few years and then disappears or reverses, but the example illustrated in figure 39 shows unusual persistence. It is taken from D–22 from 750 B. C. to 660 B. C. The even dates show less growth than the odd almost continuously for 60 years, but for the next 30 years the reverse is the case. This is evidently due to a short period of about 2 years in length. It has not yet been fully studied, but it is prominent in the European groups and in the Vermont group. It frequently shows a duration of a little less than 7 years in one phase, with odd dates greater in growth than even dates, and then for the next 7 years reverses its phase. This 14-year cycle is the series of beats the 2-year cycle produces by interfering with the exact annual and biennial effects in the tree. Hence, by a simple process, its length is found to be in effect frequently 21 or 28 months. Comparison has been made with the rainfall records near the Vermont group (Douglass, 1915 : 181) and a variable period has been found

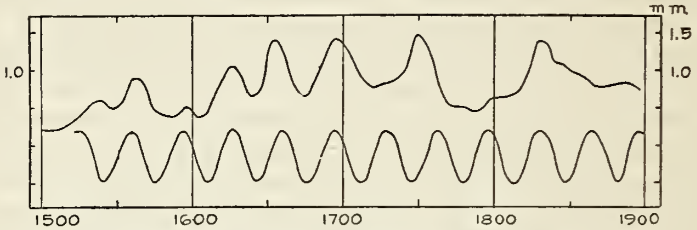

Fig. 38.—Triple sunspot cycle in a single tree from northern Norway. Lower curve, a 34-year cycle.

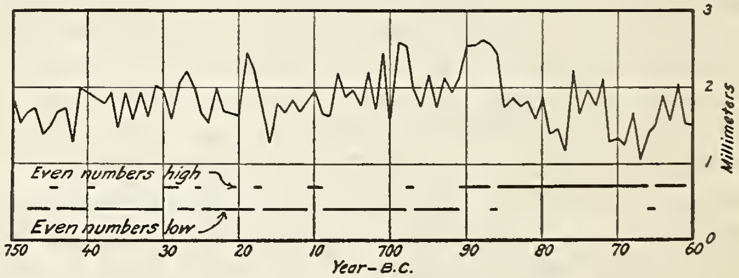

Fig. 39.—D–22 at 750 to 660 B. C., showing a 2-year period.[1]

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[1] The corrections found in 1919 make these dates one year earlier.

averaging near the larger figure. It should more properly be called a "broken" period perhaps, since it is made up of different periods for different intervals, first one and then another predominating. The methods used in the search for this 2-year period have revealed frequently a solar cycle also, and there seems to be some obscure connection between the two.

PERIODOGRAPH ANALYSES.

Differential patterns.—The periodograms, as already shown, indicate the different cycles operating within a certain range. Any one cycle together with others close to it may be studied more minutely on the differential pattern produced when the instrument is set at the desired period. Plates 12 and 10, B, are arranged to illustrate this and at the same time show the solar cycles in several of the groups. A periodic effect equal in length to the setting of the instrument is indicated by a vertical row of light crests or dark spaces. These rows may be seen in any of the patterns. If the row of crests points downward to the right, its period is greater than the setting of the instrument; if to the left, the period is less. The straightness of the row indicates the regularity of the period. Plate 12, Q, is made from the standard 5-year period with a setting at 5.0 years. The first pattern in plate 12 shows the regularity of the sunspot period since 1610 A. D. The interval in the latter part of the eighteenth century, when the cycle was reduced to less than 10 years, is distinguished by a bending of the row toward the left. This is followed by a deflection toward the right during the interval of readjustment from 1790 to 1830. The direction of any row becomes an exact measure of its period.

If a period is constant, the row of crests is straight. A zigzag row made up of short, straight parts means that one period after another becomes predominant. A curved row means a constantly changing period. Some examples of apparent curved rows may be picked out in the sequoia pattern. A curved row may indicate some other function than a simple period. Pattern *R* in plate 12 is made to illustrate a logarithmic variable, beginning at the top as a 5-year period and changing by a constant percentage increase to a 10-year period at the bottom. The instrument is set at 8.0 years.

The 11-year cycle.—The first 6 patterns in plate 12 illustrate this cycle. The first gives the sunspot numbers from 1610 to 1910, including the uncertain ones from 1610 to 1750. Pattern *B* gives the fine vertical row shown by the 6 groups of trees from north Europe. This was shown as a curve in figure 25, page 77. The qualitative test of the entire 80 European trees is shown in pattern *C*. This may be seen as a curve in figure 26. The small secondary maxima at several of the minima show as light crests between the main rows. Pattern *D* shows a 12-year period in south Sweden during the past 50 years, preceded by several maxima at about 8.5-year intervals. Pattern *E* gives the Vermont analysis. The solar cycle shows well for the last 150 years, but is preceded by a 9.2-year cycle for about 50 years, and then by the solar cycle again. This tree curve is shown in figure 27, page 78.

The Arizona pines are given in pattern *F*. The double-crested solar cycle shows in the larger part of it, but is best developed in the upper and lower thirds. By sighting along these vertical rows, a dark line in the upper third, indicating the more pronounced minimum, comes in straight line with the lesser dark minimum line in the lower third, indicating a transfer of emphasis from one-half of the 11-year cycle to the other half in passing the seventeenth century. This was noted above in connection with the analysis of the same record by a series of curves in figure 33, page 103. Further study of this pattern, however, gives information as to how and when that change took place.

Changes in the 11-year tree-cycle of Arizona—A careful examination of an early differential pattern of the Flagstaff tree record gave the following probable history of the 11-year variation in Arizona:

TABLE 7.—*Changes in the 11-year tree-cycle of Arizona.*

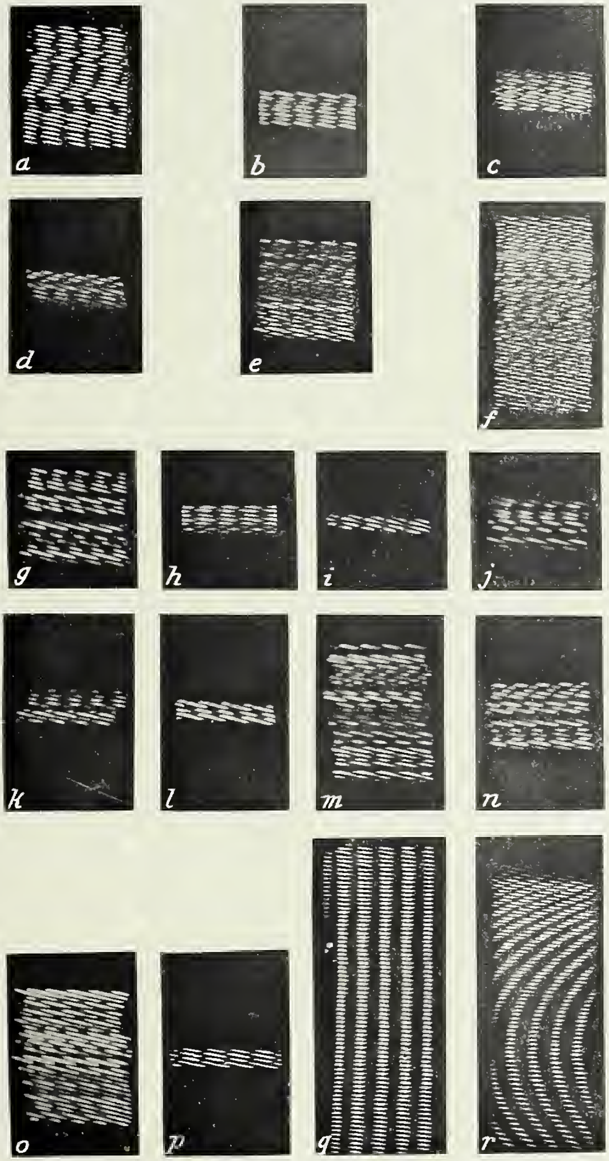
Years.	Period.	Remarks.
1395–1550	11.3	Double crests throughout, except 1476 and 1487, where the second crest fails.
1550–1595	14.3	Heavy double crest.
1595–1661	11.0±0.5	Heavy single crests with trace of double diminishing to small variable singles.
1661–1677	16.0(?)	Possibly 1 long interval.
1677–1770	12.5	Double crests mostly; going to 10.8 from 1702 to 1722.
1770–1793	9.0	Sharp single crest continuing second crest of preceding double.
1793–1817	....	Doubtful.
1817–1910	11.6	Rather broad, heavy crests, sometimes double; 1864 has too little and 1875 too much crest.

The interval from 1830 to the present time divides also extremely well on a 21.0-year period, and fairly well in one of 7.3 years.

In obtaining this result no comparison was made with the sunspot record. So the following is of interest:

TABLE 8.—*Changes in tree and sunspot cycles compared.*

Trees.		Sunspots.	
Years.	Period.	Years.	Period.
1595–1661	11.0±0.5 years.	1615.5 to 1660.0	11.1 (?) years.
1661–1677	16(?)	1660.0 to 1675.0	15.0
1677–1770	12.5 mostly and 10.8	1675.0 to 1769.7	10.5
1770–1793	9.0	1769.7 to 1788.1	9.2
1793–1817	Doubtful.	1788.1 to 1816.4	14.15
1817–1910	11.6, 21.0, or 7.3	1816.4 to 1905	11.08



DIFFERENTIAL PATTERNS.

a. Sunspot Nos. 1610–1910 at 11.4.
b. 57 European trees, 1830–1910 at 11.4.
c. 80 European trees, 1800–1910 at 11.4.
d. South Sweden, 1830–1910 at 12.0.
e. Vermont group, 1650–1910 at 11.3.
f. Flagstaff group, 500 years at 11.4.
g. Flagstaff group at 23.5 years.
h. Norway, 1740–1910 at 23.8 years.
i. Austria, 1830–1910 at 22.0 years.
j. Norway, N–2, 400 years at 33.0.
k. Vermont, 250 years at 32.5.
l. Sweden, 1740–1910 at 37.0.
m. Sequoia, 1300–250 B. C. at 33.0.
n. Flagstaff, 500 years at 33.0.
o. Sequoia, 3200 years at 101.
p. Flagstaff, 500 years at 120.
q. Standard 5-year period at 5.0 years.
r. 5 to 10 year logarithmic variable period at 8.0.

The agreement seems to the writer to justify the conclusion that the tree record may indicate a possible sunspot period of 11.3 years from 1400 to 1550 and of 14.3 from the latter date to 1600.

Sequoia pattern.—Pattern *B* in plate 10, opposite page 94, is naturally the most interesting in respect to age, as it gives the sequoia analysis for 3,200 years. The solar cycle subject to slight variations may be dimly seen in large parts of it. It shows with some prominence during the first 500 years of our era, then for a few hundred years near the year 1000 A. D., and for a long interval in the first 500 years of the record. There is opportunity for extensive study of these short periods, interpreting them by the aid of more widely scattered groups and other kinds of trees, and when possible by weather records.

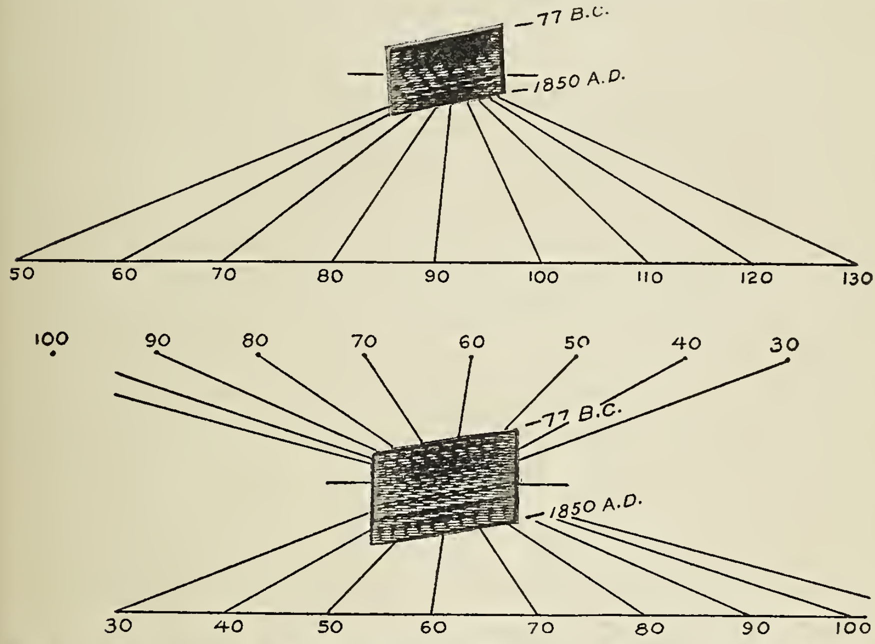


Fig. 40.—Two differential patterns of Huntington's preliminary 2000-year sequoia record. The most prominent cycle is about 105 years in length, shown in the upper diagram.

Other solar cycles.—Plate 12, G to P, shows the multiples of the solar cycle. Pattern *G* gives the Arizona tree record analyzed at 23.5 years. It shows a slightly irregular vertical row of crests. This is best seen by tipping the pattern so that the eye views it from a low angle instead of perpendicularly as in ordinary reading. A line slanting down to the left giving a period at nearly 22.2 years would answer quite as well. The lower third is somewhat broken by the triple sunspot period showing in it. The same record is analyzed at 33.0 years in pattern *N*. In this pattern the lower third shows the triple cycle in vertical rows and the double cycle shows in rows slanting strongly down to the left. Patterns *H* and *I* in plate 12 show the excellent double sunspot rhythm in the long Norwegian and shorter Austrian records, whose curves were given in figures 36 and 24 respectively, pages 105 and 77. Pattern *J* shows the 33-year cycle of the 400-year tree, N–2, from near the Arctic Circle in Norway. The Vermont hemlocks are shown in pattern *K*. Here is found a good rhythm with a change in phase about 100 years ago. The Swedish curve shows a good rhythm at 37 years. Several intervals of triple solar cycle appear in the 1,000 years of early sequoia growth in pattern *M*. All the 8 patterns *G* to *N* are taken from special curves prepared on a one-fifth scale, using 5-year sums in the plot.

The 100-year cycle.—Only two tree records are long enough to be tested for a cycle of this length. The sequoia gives a very excellent alinement at a period of 101 years, shown even better in the upper pattern of figure 40. The pattern of the present plate shows an increase to about 125 years in the last 600 years, which corresponds to the best analysis of the 500-year Arizona curve. This latter is at 120 years as shown in pattern *P*. Both of these are made from special curves plotted on one twenty-fifth of the usual scale.

Illustration by the periodograph.—The illustrations of periodograph analysis given above are practically the first made with this instrument and are therefore crude in many respects. Its advantage in the study of simple and obvious cycles such as the sunspot numbers is not at once apparent to the eye and its efficiency becomes evident only when one tries to select the exact period and state its accuracy. But one can foresee a useful application of this instrument in the study of mixed periods, such as appear in tree-growth here considered or in rainfall and other meteorological elements, a field as yet almost untouched on account of its complexity. However, in the brief presentation of its work given above, it is evident that the periodograph is found to corroborate and extend the results of the previous direct study of curves and to confirm the evidence there given of the great extent and importance of the solar cycles in the growth of trees.

SUMMARY.

In the foregoing investigation the following conclusions have been reached:

(1) The variations in the annual rings of individual trees over considerable areas exhibit such uniformity that the same rings can be identified in nearly every tree and the dates of their formation established with practical certainty.

(2) In dry climates the ring thicknesses are proportional to the rainfall with an accuracy of 70 per cent in recent years and this accuracy presumably extends over centuries; an empirical formula can be made to express still more closely this relationship between tree-growth and rainfall; the tree records therefore give us reliable indications of climatic cycles and of past climatic conditions.

(3) The tree's years for such records begins in the autumn.

(4) Double rings are caused by spring drought and are indicative of the distribution of rainfall throughout the year.

(5) Tree records may be used in the intensive study of the location of homogeneous meteorological conditions and in outlining meteorological districts.

(6) Certain areas of wet-climate trees in northern Europe give an admirable record of the sunspot numbers and some American wet-climate trees give a similar record, but with their maxima 1 to 3 years in advance of the solar maxima. It is possible to identify living trees giving this remarkable record and to ascertain the exact conditions under which they grow.

(7) Practically all the groups of trees investigated show the sunspot cycle or its multiples; the solar cycle becomes more certain and accurate as the area of homogeneous region increases or the time of a tree record extends farther back; this suggests the possibility of determining the climatic and vegetational reaction to the solar cycle in different parts of the world.

(8) A most suggestive correlation exists in the dates of maxima and minima found in tree-growth, rainfall, temperature and solar phenomena. The prevalence of the solar cycle or its multiples, the greater accuracy as area or time are extended, and this correlation in dates point toward a physical connection between solar activity and terrestrial weather.

(9) The tree curves indicate a complex combination of short periods including a prominent cycle of about 2 years.

(10) An instrument has been constructed which promises special facility in the analysis of such periods.

The items enumerated above point to the general conclusion that near at hand and readily available in our forest areas is written a story of climatic cycles and solar relationship which in part at least is interpreted by the methods illustrated in the foregoing pages.

ADDENDUM.

In the summer of 1919 a trip was made to the sequoia groves with three objects in view: (1) settling an uncertainty regarding the ring provisionally called 1580 A; (2) gathering material bearing on the relation of short-period cycles to topography; (3) investigating the causes of enlarged or gross rings. It is only the first of these topics which has an important bearing on the foregoing chapters.

The region near the General Grant National Park was visited and 12 new trees were very carefully selected as to their water-supply, drainage, and distance from other trees, and short radial samples were cut from them. It did not seem necessary to have these include more than the last 500 years of growth. The radial piece, therefore, was made very small, but especial attention was given to procuring a continuous and reliable record. Critical examination showed at once that occurrence of the ring 1580 A was dependent on locality. The trees from the uplands, where identification was easy, largely failed to show the ring, but in specimens from swampy basins, where cross-identification was difficult and sometimes uncertain, the ring was nearly always present. A complete decision, therefore, in favor of its real existence was satisfactorily obtained and the necessary corrections were made in the foregoing text and in the tabular matter which follows. It seems likely that the year 1580, which this ring represents, was phenomenally deficient in moisture in the locality of these giant trees.

In addition to the 12 new trees added to the sequoia group, a cutting was made from the stump D-12, which had hitherto defied all attempts at satisfactory dating. A small piece going back about 800 years was cut from a part of the circumference, entirely free from compressed rings, about 4 feet away from the full sample cut in 1915. At the time of cutting, great care was taken to insure proper cross-identification between the inner end of the new piece and the former sample. But in the laboratory the new piece proved to carry a very excellent series of rings and the identification was everywhere very easy and sure, and all doubt about the dating of that particular tree to its earliest ring in 135 A. D., several inches away from its original center, was removed; therefore, it may now be included among those whose dating is entirely reliable.

A new group of 5 very old trees from near Flagstaff, has settled an uncertainty regarding the years 1463 and 1464 in the yellow pines (too late, however, to rectify figure 3 on page 25). It is now possible to carry a very fair cross-identification between the pines of Arizona and the sequoias of California through the whole five centuries of the former.

APPENDIX.

TABLES OF MEAN TREE-GROWTH, BY GROUPS.

The tables give the mean growth of the group for each year in millimeters. The decade number in the left column applies to the growth in the adjacent column, and the succeeding 9 years follow along the horizontal line.

Flagstaff 500–year measures: 2 to 19 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1390	......	......	1.55	2.25	2.50	1.75	2.20	2.30	2.20	2.10
1400	2.55	2.75	2.00	2.10	1.95	1.90	2.30	1.50	2.35	1.65
1410	1.65	2.25	1.90	1.80	1.85	1.30	2.25	1.30	1.90	1.10
1420	0.80	0.70	0.90	1.90	1.45	1.40	1.20	1.35	1.55	1.80
1430	1.25	1.65	1.15	1.45	1.95	0.75	1.20	1.35	0.80	0.90
1440	1.35	1.25	0.60	0.65	1.40	1.10	1.00	1.05	0.95	1.60
1450	1.25	1.40	1.85	1.60	1.15	0.85	1.35	1.65	1.20	0.80
1460	0.80	1.25	1.75	1.40	0.55	0.95	1.40	1.45	1.10	1.60
1470	1.25	1.05	1.10	1.65	1.00	1.00	1.25	1.40	1.40	1.45
1480	1.20	1.10	1.35	1.00	1.05	0.60	1.05	0.40	0.60	1.05
1490	1.40	1.80	1.10	0.85	1.40	0.70	1.10	1.35	1.65	0.60
1500	0.40	1.55	1.15	0.70	1.35	0.80	0.50	1.25	1.10	1.05
1510	0.55	1.05	0.55	1.05	0.90	0.90	0.65	0.45	0.75	1.32
1520	1.06	0.96	0.72	0.96	0.98	1.36	1.56	1.22	0.82	1.50
1530	1.38	1.16	0.74	0.92	0.94	1.10	1.54	1.22	0.74	1.34
1540	1.50	1.40	0.86	1.14	1.32	1.00	1.62	1.28	1.10	1.72
1550	1.66	1.76	2.02	1.80	1.60	1.56	1.32	1.18	0.78	1.34
1560	1.48	1.34	1.72	1.84	1.70	1.68	1.20	1.30	1.94	1.80
1570	1.20	1.68	1.44	1.02	1.08	1.00	0.98	1.34	1.04	1.08
1580	0.78	1.18	1.34	1.26	0.36	0.22	0.88	1.30	1.76	1.76
1590	0.92	0.70	1.14	1.68	1.66	1.70	1.28	1.44	1.34	1.60
1600	0.34	0.84	0.96	1.44	1.22	1.20	1.38	1.14	1.20	1.72
1610	1.66	1.14	1.10	0.78	1.18	0.98	1.48	1.62	1.72	1.48
1620	1.78	1.60	1.22	0.70	1.04	1.18	0.88	0.90	0.80	1.08
1630	0.98	0.70	0.26	0.72	0.82	0.98	0.80	0.68	0.62	0.86
1640	1.16	0.90	1.08	1.02	1.04	0.84	0.76	0.76	0.60	0.78
1650	1.10	1.12	0.86	0.64	0.36	0.80	0.72	0.74	0.82	0.96
1660	0.94	0.96	0.96	1.24	0.86	0.92	0.68	0.68	0.64	0.46
1670	0.32	0.54	0.80	1.04	1.38	1.06	0.86	0.94	0.96	0.88
1680	1.26	1.26	0.74	1.04	0.72	0.74	0.62	1.00	1.00	1.06
1690	0.86	0.96	0.98	0.96	1.14	0.94	0.84	0.94	1.06	1.14
1700	1.18	1.08	0.98	0.86	1.28	1.30	1.48	0.74	0.94	1.02
1710	1.06	0.80	1.02	1.12	0.94	1.04	0.98	1.00	1.36	1.10
1720	1.24	0.82	0.86	1.12	0.98	1.40	1.40	0.62	0.64	0.42
1730	0.56	0.72	0.82	0.64	0.86	0.32	0.88	0.56	0.96	0.54
1740	0.82	0.80	0.76	0.90	0.74	0.78	1.06	0.84	0.40	0.86
1750	0.70	0.66	0.10	0.68	0.62	0.62	0.44	0.74	1.00	0.76
1760	0.80	0.92	0.90	0.88	1.22	0.94	0.86	0.86	0.68	0.66
1770	0.80	0.68	0.76	0.36	0.60	0.74	0.72	0.64	0.48	0.48
1780	0.36	0.52	0.32	0.74	1.02	0.50	0.60	0.86	0.54	0.50
1790	0.58	0.72	0.76	0.90	0.86	0.80	0.58	0.70	0.42	0.74
1800	0.58	0.44	0.78	0.56	0.50	0.78	0.78	0.54	0.58	0.80
1810	0.76	0.76	0.62	0.22	0.42	0.58	0.64	0.52	0.36	0.62
1820	0.36	0.62	0.04	0.46	0.48	0.50	0.72	0.68	0.74	0.42
1830	0.94	0.88	0.82	0.64	0.56	0.66	0.64	0.60	0.54	0.64
1840	0.60	0.44	0.30	0.56	0.52	0.34	0.42	0.36	0.66	0.56
1850	0.68	0.22	0.82	0.86	0.90	0.76	0.62	0.70	0.64	0.70
1860	0.88	0.52	0.74	0.62	0.62	0.56	0.86	0.64	0.94	0.62
1870	0.86	0.68	0.64	0.52	0.80	0.56	0.52	0.46	0.52	0.26
1880	0.34	0.44	0.36	0.36	0.42	0.46	0.32	0.40	0.48	0.46
1890	0.54	(0.47)	(0.35)	(0.35)	(0.45)	(0.40)	(0.54)	0.40	0.60	0.40
1900	0.40	0.54	0.20	0.36	0.20	0.32	0.42	(0.53)	(0.60)	(0.66)
1910	(0.73)	......	......	......	......	......	......	......	......	......

South of England: 11 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1850	......	......	......	......	......	......	......	......	......	3.1
1860	5.1	4.6	4.7	3.8	3.53	4.18	4.29	5.25	4.27	4.32
1870	3.65	5.19	5.21	4.32	4.34	4.87	4.04	3.79	4.94	4.72
1880	3.26	3.75	3.93	3.50	3.12	2.78	3.08	2.23	2.06	1.75
1890	2.41	1.74	1.81	1.81	2.30	2.22	2.06	1.83	1.48	1.45
1900	1.71	1.90	1.63	2.35	2.29	1.83	1.84	1.65	1.72	1.51
1910	2.28	1.71	1.65	......	......	......	......	......	......	......

Outer Coast of Norway: 10 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1820	......	......	......	......	......	......	......	......	0.75	0.62
1830	0.38	0.38	0.38	0.25	0.50	0.50	0.75	0.75	0.50	0.62
1840	0.50	0.75	0.75	0.88	1.38	1.53	1.57	1.68	1.44	1.47
1850	1.50	1.39	1.59	1.22	1.74	1.29	1.17	1.01	1.28	1.57
1860	1.57	1.24	1.26	1.28	1.27	1.40	1.54	1.52	1.85	1.77
1870	1.57	1.87	2.18	1.83	2.10	1.35	1.38	1.22	1.58	0.98
1880	1.25	0.73	1.11	1.14	1.64	1.09	1.29	1.20	1.17	1.27
1890	0.86	1.07	1.05	1.21	1.18	0.97	1.07	1.16	1.20	1.02
1900	0.85	0.90	0.69	1.14	1.24	1.34	1.20	1.05	1.13	0.66
1910	1.03	0.70	0.94	......	......	......	......	......	......	......

Inner Coast of Norway: 8 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1820	1.81	2.38	2.09	2.22	2.25	2.00	2.12	1.89	2.04	1.88
1830	2.00	1.89	1.72	2.01	1.80	1.45	1.30	1.64	1.81	1.65
1840	1.60	1.78	1.92	2.15	2.08	1.94	1.94	1.81	1.81	1.81
1850	1.71	1.66	1.79	1.40	1.69	1.58	1.40	1.54	1.49	1.22
1860	1.56	1.31	1.52	1.65	1.62	1.68	1.74	1.65	1.66	1.34
1870	1.56	1.26	1.38	1.44	1.75	1.60	1.48	1.76	2.16	1.68
1880	1.89	1.34	1.52	1.38	1.36	1.29	1.25	1.22	1.34	1.36
1890	1.44	1.44	1.51	1.45	1.79	1.30	1.10	1.05	1.08	1.00
1900	0.95	1.19	1.14	1.30	1.29	1.20	1.10	1.00	1.14	......

Christiania: 5 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1820	1.12	1.06	1.10	1.10	1.16	1.10	1.60	1.54	1.60	1.48
1830	1.28	1.12	0.94	0.86	0.96	1.12	1.22	1.20	1.08	1.68
1840	1.52	1.70	2.32	1.76	1.82	1.58	1.36	1.44	1.66	1.40
1850	1.54	1.60	1.36	1.26	1.72	1.36	1.20	1.32	1.32	1.52
1860	1.66	1.48	1.58	1.40	1.72	1.52	1.58	1.50	1.96	1.94
1870	2.00	1.60	1.14	1.50	1.62	1.64	1.20	1.68	1.84	1.18
1880	1.70	1.84	2.10	1.86	2.26	2.12	2.08	1.88	1.42	1.42
1890	1.24	1.10	1.28	1.62	1.60	1.48	1.56	1.44	1.14	1.22
1900	1.14	1.24	1.00	1.36	1.16	1.30	1.36	1.28	1.86	1.88
1910	2.68	2.36	2.34	......	......	......	......	......	......	......

Central Sweden: 12 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1820	0.92	0.92	1.05	1.08	1.16	0.98	1.12	1.08	1.12	0.84
1830	0.97	0.92	0.74	0.93	1.04	0.65	0.72	0.72	0.72	0.69
1840	0.71	0.65	0.78	0.71	0.77	0.66	0.72	0.62	0.81	0.77
1850	0.78	0.70	0.66	0.46	0.73	0.62	0.82	0.89	0.98	1.12
1860	1.30	1.14	1.04	1.04	0.96	0.95	1.02	0.87	1.09	0.97
1870	1.28	1.03	1.02	0.85	0.88	0.87	0.87	0.86	0.93	0.76
1880	0.84	0.66	0.86	0.68	0.77	0.88	0.84	0.88	0.76	0.74
1890	0.74	0.76	0.81	0.78	0.92	0.89	0.92	0.77	0.62	0.70
1900	0.67	0.74	0.50	0.59	0.58	0.53	0.51	0.47	0.47	0.46
1910	0.55	......	......	......	......	......	......	......	......	......

South Sweden: 6 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1820	1.90	1.75	1.85	1.98	2.15	2.25	1.78	1.82	1.58	1.72
1830	2.37	2.37	1.68	1.83	1.95	1.58	1.55	1.58	1.85	1.87
1840	1.93	2.07	1.82	1.23	1.35	1.27	1.45	1.02	1.87	1.38
1850	1.25	1.23	1.23	1.20	1.08	1.48	1.20	1.28	1.42	1.35
1860	1.35	1.28	1.68	1.65	1.35	1.43	1.42	1.07	1.42	1.23
1870	1.45	1.37	1.32	1.08	1.00	1.03	0.95	0.93	1.03	1.02
1880	1.23	1.12	1.38	1.02	1.28	1.02	0.90	0.72	0.82	0.78
1890	0.72	0.88	0.88	1.03	1.02	0.90	0.97	0.92	0.87	0.70
1900	0.78	0.93	0.68	0.77	0.63	0.72	0.73	0.77	0.82	0.80
1910	0.70	......	......	......	......	......	......	......	......	......

Eberswalde, Prussia: 13 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1830	2.70	2.56	2.78	2.26	2.52	2.38	2.79	3.22	3.74	3.04
1840	2.63	2.38	1.56	2.11	2.55	2.06	2.55	1.82	2.82	2.88
1850	2.08	2.15	1.55	1.96	1.66	1.05	1.06	0.87	1.28	1.92
1860	1.98	2.15	1.88	1.51	1.49	1.40	1.22	1.68	1.33	1.54
1870	1.59	1.58	1.52	1.16	1.35	1.46	1.25	0.83	1.25	1.23
1880	1.12	1.31	2.13	1.47	2.06	1.68	1.29	1.05	0.99	0.91
1890	1.12	1.37	0.97	0.85	0.55	0.63	0.79	0.63	0.78	0.73
1900	0.69	0.62	0.73	1.17	1.03	1.12	0.91	0.93	0.57	0.42
1910	0.47	0.35	0.58	......	......	......	......	......	......	......

Pilsen, Austria: 7 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1830	4.03	3.99	2.74	3.60	3.49	2.59	2.06	3.36	2.47	2.43
1840	2.79	3.01	1.66	2.29	2.66	1.63	2.17	1.64	1.34	0.89
1850	1.13	1.54	1.50	1.60	1.59	1.54	1.70	1.06	1.33	1.23
1860	1.44	1.31	1.54	1.43	0.74	0.99	1.27	1.39	0.99	1.20
1870	1.09	1.29	1.44	1.19	0.87	1.14	1.30	1.14	1.51	1.24
1880	1.50	1.37	1.70	1.56	1.70	1.33	1.37	0.93	1.00	0.87
1890	1.17	1.16	1.26	1.16	1.31	1.41	1.49	1.70	1.40	1.50
1900	1.47	1.40	1.20	1.19	0.97	1.04	1.09	1.04	0.89	1.03
1910	1.23	0.91	1.31	......	......	......	......	......	......	......

Southern Bavaria: 8 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1840	......	......	......	......	......	......	......	......	3.20	3.42
1850	3.36	3.71	3.31	3.64	3.41	2.80	2.62	2.42	2.14	1.95
1860	1.91	2.35	2.38	1.98	1.90	1.08	1.38	1.28	1.35	1.42
1870	1.09	1.75	1.71	1.62	1.39	1.39	1.52	1.58	1.68	1.66
1880	1.65	1.55	1.50	1.44	1.26	1.05	1.00	0.92	1.09	0.96
1890	1.11	0.99	1.04	0.76	0.81	0.96	0.95	0.96	0.95	0.72
1900	0.81	0.82	0.74	0.86	0.90	0.81	1.02	1.19	0.92	0.66
1910	0.79	0.76	......	......	......	......	......	......	......	......

Six old Norway trees: Group A; inner coast.

A. D.	0	1	2	3	4	5	6	7	8	9
1740	1.10	0.98	0.82	0.84	0.78	1.00	1.03	1.40	1.30	1.25
1750	1.52	1.35	1.73	1.55	2.07	1.83	1.15	1.85	1.55	1.45
1760	1.77	1.48	1.20	1.30	1.11	0.98	1.45	1.43	1.60	1.52
1770	1.30	1.52	1.48	1.45	1.42	1.95	1.80	1.75	1.47	1.43
1780	1.43	1.30	0.97	0.87	0.82	0.78	0.68	0.82	0.72	0.80
1790	0.97	1.02	1.23	1.02	0.97	1.08	1.22	1.07	1.35	1.50
1800	2.03	1.70	1.35	1.27	1.08	1.23	1.33	1.15	1.17	1.02
1810	1.00	0.82	0.90	1.28	1.32	1.22	1.13	1.58	1.23	1.18
1820	1.73	2.05	1.77	1.67	1.82	1.63	2.02	1.82	2.00	1.77
1830	1.73	1.84	1.80	1.88	1.64	1.28	......	......	......	......

Eight old Sweden trees; Group B; Dalarne.

A. D.	0	1	2	3	4	5	6	7	8	9
1740	0.70	0.54	0.54	0.73	0.85	0.90	0.87	0.90	1.00	0.87
1750	1.09	0.90	1.07	0.79	0.80	0.78	0.55	0.61	0.65	0.87
1760	0.80	0.86	1.00	0.92	0.87	0.90	0.99	0.95	0.92	0.76
1770	0.62	0.66	0.71	0.75	0.68	0.82	0.88	0.90	0.93	0.97
1780	0.89	0.86	0.92	0.89	0.95	0.86	0.79	0.86	0.81	0.68
1790	0.68	0.78	0.67	0.62	0.68	0.59	0.68	0.63	0.63	0.63
1800	0.56	0.52	0.61	0.55	0.58	0.58	0.52	0.60	0.57	0.59
1810	0.58	0.65	0.71	0.74	0.71	0.73	0.68	0.73	0.81	0.79
1820	0.66	0.63	0.66	0.66	0.75	0.61	0.81	0.75	0.82	0.65
1830	0.62	0.65	0.55	0.70	0.79	0.55	......	......	......	......

Windsor, Vermont; 11 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1650	......	0.6	0.8	0.7	0.72	0.47	1.03	0.77	0.67	0.75
1660	0.68	0.62	0.28	0.38	0.45	0.35	0.55	0.40	0.28	0.53
1670	0.22	0.38	0.29	0.35	0.45	0.37	0.40	0.39	0.50	0.48
1680	0.57	0.52	0.38	0.35	0.40	0.37	0.42	0.41	0.49	0.72
1690	0.76	0.40	0.57	0.73	0.73	1.06	0.79	0.65	0.57	0.72
1700	0.67	0.64	0.54	0.50	0.26	0.20	0.34	0.36	0.37	0.45
1710	0.37	0.47	0.49	0.45	0.60	0.47	0.66	0.75	1.03	0.84
1720	0.70	0.90	0.83	0.57	0.88	0.99	0.92	1.15	0.79	0.68
1730	0.87	0.89	0.54	0.51	0.66	0.69	0.68	0.60	0.67	0.56
1740	0.51	0.34	0.47	0.37	0.52	0.65	0.56	0.72	0.41	0.47
1750	0.55	0.71	0.76	0.62	0.53	0.51	0.81	1.04	0.92	1.12

Windsor, Vermont; 11 trees—continued.

A. D.	0	1	2	3	4	5	6	7	8	9
1760	1.12	0.96	0.73	0.78	1.00	1.05	0.65	0.62	0.74	0.91
1770	0.44	0.45	0.53	0.54	0.59	0.58	0.67	0.81	0.86	0.80
1780	0.67	0.77	0.86	0.75	0.51	0.53	0.74	0.60	0.71	0.81
1790	0.57	0.54	0.58	0.69	0.63	0.69	0.61	0.50	0.46	0.47
1800	0.66	0.82	0.72	0.77	0.61	0.96	0.82	1.25	1.94	2.02
1810	1.96	2.09	1.95	1.85	1.75	1.86	1.47	1.46	1.28	1.43
1820	1.21	0.79	2.06	1.81	2.41	1.88	1.40	2.05	2.62	2.18
1830	2.56	2.66	2.17	2.71	2.65	1.85	1.62	1.74	2.26	1.85
1840	2.00	1.75	1.51	1.70	2.07	1.95	1.90	2.11	2.06	1.74
1850	1.77	2.33	1.66	1.36	1.39	1.50	1.70	1.77	1.99	1.45
1860	1.63	2.12	1.37	1.76	1.61	1.79	1.78	1.75	2.33	1.55
1870	1.67	1.32	1.25	1.04	1.76	1.73	1.49	1.21	1.97	1.58
1890	2.23	1.68	1.97	1.15	1.68	0.93	1.49	1.73	1.50	2.37
1890	2.04	2.31	2.76	2.11	2.75	1.23	1.38	2.01	2.11	1.06
1900	1.19	1.35	1.61	1.79	1.43	1.38	1.39	1.25	1.13	1.20
1910	1.51	0.95	1.76	......	......	......	......	......	......	......

Oregon group; 17 trees.

A. D.	0	1	2	3	4	5	6	7	8	9
1710	4.21	4.04	3.91	4.30	4.44	4.81	5.21	4.30	3.63	4.38
1720	4.57	4.08	4.31	4.10	4.06	4.21	3.84	3.84	3.62	3.67
1730	3.69	3.39	3.63	3.49	3.14	2.80	2.89	2.74	2.97	3.46
1740	2.34	2.19	2.02	2.16	2.29	2.17	1.91	2.09	2.14	2.36
1750	2.29	2.57	2.52	2.67	2.17	1.92	2.00	1.98	1.90	1.99
1760	2.33	2.18	2.33	2.28	2.49	2.18	2.27	2.33	2.26	2.32
1770	2.69	3.16	3.15	3.01	3.32	2.85	3.22	2.84	3.04	3.25
1780	3.15	3.23	2.72	2.52	2.62	3.05	3.58	3.35	2.58	3.28
1790	2.74	2.46	2.59	2.74	3.00	2.78	2.59	2.36	2.29	2.50
1800	2.45	2.44	2.57	2.61	2.65	2.81	2.97	2.52	2.57	2.31
1810	2.37	2.31	2.06	2.11	2.35	2.71	2.77	2.62	2.48	2.54
1820	2.99	2.72	1.96	2.36	2.10	2.38	2.37	2.54	2.22	2.05
1830	2.19	2.21	2.06	2.80	2.72	2.29	2.53	2.15	2.21	2.35
1840	2.22	2.00	1.82	1.88	1.52	1.86	2.08	2.42	1.93	1.94
1850	1.33	1.66	1.74	1.75	1.76	1.84	2.05	2.11	1.93	1.77
1860	1.88	2.24	2.32	1.84	1.92	1.81	1.76	1.88	2.31	2.01
1870	1.76	1.61	1.56	1.60	1.66	1.75	2.07	2.08	2.13	2.15
1880	2.12	1.88	1.62	1.50	1.08	1.09	1.16	1.44	1.34	1.88
1890	1.54	1.25	1.62	1.84	1.68	1.68	1.48	1.19	0.98	1.62
1900	1.54	1.89	1.78	1.61	1.87	1.77	1.31	1.28	1.39	1.34
1910	1.11	1.11	......	......	......	......	......	......	......	......

Sequoia record: Group of 1918; 1 to 4 trees.

B. C.	0	9	8	7	6	5	4	3	2	1
1310	......	......	......	......	[1]1.10	2.90	2.50	1.50	2.40	2.60
1300	2.45	1.40	1.30	1.25	1.25	1.00	0.90	1.30	1.20	1.30
1290	1.50	1.40	1.45	1.15	1.10	0.95	0.90	1.00	0.90	0.85
1280	1.15	1.20	1.05	1.20	1.00	0.75	0.60	0.75	0.65	0.90
1270	0.65	0.40	0.55	0.55	0.50	0.70	0.90	0.55	0.55	0.80
1260	0.90	0.55	0.70	0.80	0.80	0.95	1.05	0.60	0.50	0.45
1250	0.70	0.70	0.60	0.70	0.80	0.80	0.60	0.90	0.70	0.60
1240	0.70	0.45	0.75	0.85	1.15	0.85	0.90	1.00	0.90	1.15
1230	1.25	1.35	1.40	1.40	1.55	2.10	2.20	2.85	3.45	3.10

[1] 1306 B. C. is incomplete.

Sequoia record: Group of 1918; 1 to 4 trees—continued.

B. C.	0	9	8	7	6	5	4	3	2	1
1220	3.25	3.45	2.85	3.00	3.50	3.65	4.55	3.50	3.80	3.35
1210	3.35	3.95	3.10	4.20	4.00	3.90	2.95	2.75	3.20	2.20
1200	2.50	3.20	2.80	3.35	3.75	3.25	2.85	3.35	3.35	4.30
1190	3.35	2.90	3.65	3.95	3.95	3.05	3.05	3.00	3.45	4.25
1180	4.10	3.95	4.00	3.10	3.25	3.75	4.40	3.70	5.00	4.20
1170	3.60	3.10	2.50	2.85	3.65	4.10	3.15	3.50	3.10	2.40
1160	2.30	2.65	2.80	3.10	2.65	2.30	2.30	2.30	3.15	2.50
1150	2.20	2.55	3.10	3.05	3.80	2.85	2.75	2.80	2.80	3.10
1140	3.25	2.50	2.50	2.75	2.65	2.90	3.50	3.15	2.40	2.35
1130	2.80	2.45	3.00	2.75	2.55	3.50	3.25	2.35	2.18	2.59
1120	2.26	2.12	2.09	1.71	1.86	2.04	2.09	2.54	1.76	2.06
1110	1.72	1.99	2.42	2.23	1.98	1.90	1.55	1.85	2.04	2.23
1100	2.15	2.30	2.58	2.53	2.42	1.84	1.99	1.93	2.32	2.14
1090	1.55	1.67	1.78	1.69	1.91	1.78	1.62	1.44	1.59	1.68
1080	1.68	1.66	1.51	1.64	1.48	1.77	1.88	2.72	2.71	2.66
1070	2.04	2.76	1.01	1.08	1.30	0.97	1.18	1.14	1.34	1.43
1060	1.34	1.38	1.22	1.32	1.74	1.76	1.77	1.54	1.31	1.13
1050	1.34	1.31	1.53	1.69	1.63	1.41	1.45	1.60	1.59	1.31
1040	1.79	1.41	1.45	1.27	1.23	1.25	1.29	1.01	1.68	1.68
1030	1.66	1.92	1.65	1.74	1.53	1.56	1.50	1.19	1.09	1.33
1020	0.99	1.22	1.27	1.24	1.67	1.33	1.66	1.92	2.12	2.10
1010	1.87	1.64	1.22	1.29	1.12	1.08	1.24	1.44	1.39	1.33
1000	1.29	1.28	1.28	1.20	1.24	1.24	1.29	1.65	1.31	1.29
990	1.24	1.29	1.19	1.34	1.39	1.28	1.21	1.24	1.10	1.15
980	1.06	1.14	1.00	1.38	1.21	1.25	1.12	1.20	1.24	1.32
970	1.37	1.27	1.30	1.04	1.27	1.24	1.16	1.20	1.36	1.18
960	1.25	1.30	1.32	1.43	0.76	0.83	1.03	0.93	1.10	1.07
950	1.35	1.56	1.55	1.30	1.32	1.64	1.43	1.83	1.51	1.38
940	1.44	1.16	1.50	1.37	1.63	1.91	2.35	2.20	2.17	1.74
930	2.09	2.79	3.23	2.66	1.77	2.06	1.76	1.78	2.13	1.85
920	2.14	2.02	1.69	1.71	1.70	1.22	1.46	1.71	1.88	1.64
910	1.86	1.87	2.18	1.72	1.44	1.77	1.92	1.82	1.80	1.87
900	2.25	2.35	2.29	1.98	2.10	2.37	2.32	2.07	2.45	2.10
890	1.89	1.96	1.94	1.95	2.40	2.18	2.12	2.24	2.33	1.95
880	2.17	2.29	2.48	2.13	2.11	2.33	1.99	1.77	1.83	1.67
870	1.62	1.72	2.17	1.58	1.43	1.19	1.31	1.36	1.30	1.38
860	1.30	1.42	1.33	1.25	1.14	1.13	1.09	1.15	1.11	0.74
850	1.02	1.23	1.14	1.07	1.04	1.39	1.32	1.45	1.42	1.58
840	1.32	1.51	1.54	1.40	1.40	1.36	1.40	1.43	1.44	1.28
830	1.57	1.51	1.28	1.16	1.57	1.65	1.54	1.32	1.22	1.26
820	1.06	1.12	1.11	0.97	0.97	1.00	0.98	1.11	1.00	1.01
810	1.15	1.25	1.30	1.04	1.18	1.10	0.88	1.07	1.13	1.20
800	1.10	1.18	1.27	1.20	1.14	1.26	1.26	1.26	1.08	1.26
790	1.10	1.04	1.19	1.07	1.16	1.21	1.02	1.08	1.08	1.10
780	1.03	1.21	1.16	0.92	0.91	1.12	1.23	1.08	0.89	1.03
770	1.06	1.25	1.07	1.02	1.12	1.14	1.09	1.28	1.17	1.31
760	1.27	1.22	1.41	1.04	1.22	1.12	1.08	1.06	1.23	1.27
750	1.27	1.35	1.38	1.12	1.15	1.59	1.37	1.10	1.44	1.48
740	1.53	1.33	1.30	1.25	1.46	1.29	1.32	1.30	1.47	1.28
730	1.26	1.40	1.62	1.46	1.17	1.23	1.49	1.38	1.21	0.94
720	1.52	1.46	1.39	1.02	1.19	1.20	1.34	1.30	1.22	1.44
710	1.37	1.43	1.58	1.52	1.72	1.32	1.51	1.26	1.60	1.33
700	1.82	1.56	1.30	1.43	1.45	1.66	1.40	1.45	1.79	1.81
690	1.78	1.75	1.79	1.78	1.36	1.46	1.42	1.52	1.28	1.40
680	1.21	1.26	1.09	1.41	1.25	1.30	1.44	1.63	1.28	1.51
670	1.25	1.38	1.06	1.20	1.30	1.25	1.34	1.70	1.44	1.15
660	1.35	1.20	1.22	1.01	0.96	1.13	1.44	1.36	1.20	1.32
650	1.18	1.22	0.86	1.18	0.97	1.03	1.12	0.98	1.01	1.14
640	1.14	1.32	1.17	1.08	1.12	1.18	1.16	1.14	1.04	0.94
630	1.22	1.02	0.98	1.02	1.00	1.24	1.21	1.18	1.10	1.39
620	1.24	1.22	1.26	1.13	1.13	1.20	1.22	1.08	1.08	1.19
610	1.08	0.90	1.02	0.95	1.07	1.15	1.05	1.04	0.96	1.21

Sequoia record: Group of 1918, 1 to 4 trees—continued.

B. C.	0	9	8	7	6	5	4	3	2	1
600	1.25	1.20	0.95	1.10	0.90	0.90	1.05	1.08	0.94	0.99
590	0.94	1.06	0.83	0.82	0.97	0.92	0.60	0.64	0.45	0.68
580	0.83	0.96	0.75	0.78	0.96	0.80	0.82	0.83	0.90	0.86
570	0.76	1.02	0.91	0.74	0.86	0.93	0.93	0.86	0.78	0.81
560	0.66	0.80	0.82	0.95	0.88	0.95	0.96	1.11	1.03	1.10
550	1.21	1.44	1.38	1.32	1.29	1.26	1.10	1.18	1.34	1.19
540	1.10	0.94	1.07	0.76	0.79	0.89	0.66	0.77	1.05	1.04
530	1.00	0.88	0.90	1.01	0.81	0.90	0.80	0.82	0.88	0.94
520	0.60	0.74	1.01	0.99	0.93	0.92	0.83	0.87	0.50	0.96
510	1.08	0.96	0.91	1.02	1.06	1.12	1.04	1.01	1.10	1.29
500	0.98	1.00	1.01	0.89	0.90	1.10	1.10	1.09	1.02	0.91
490	1.14	1.10	1.06	1.03	0.90	0.92	1.00	0.94	1.05	1.12
480	1.17	1.12	1.10	1.11	1.22	1.04	1.08	0.88	0.82	0.90
470	0.91	1.03	0.99	1.01	1.16	0.76	0.96	0.80	0.82	0.94
460	0.96	0.91	0.79	0.84	0.79	0.90	0.84	0.82	0.69	0.86
450	0.84	0.60	0.66	0.79	0.83	0.86	0.77	0.78	0.86	0.77
440	0.84	0.94	0.94	0.78	0.79	0.80	0.80	1.02	1.09	1.12
430	1.16	0.81	0.97	0.86	0.82	0.75	0.88	0.69	0.63	0.58
420	0.90	0.60	0.73	0.83	0.58	0.77	0.88	0.78	0.74	0.84
410	0.89	0.59	0.82	0.90	1.05	0.93	0.82	0.90	0.83	0.83
400	0.83	0.75	0.80	0.67	0.66	0.55	0.71	0.75	0.58	0.78
390	0.90	0.74	0.66	0.77	0.80	0.76	0.69	0.99	0.83	0.80
380	0.75	0.95	1.02	0.99	1.04	0.91	0.95	0.88	0.92	1.09
370	1.00	1.00	0.90	0.97	0.92	1.01	0.87	0.81	0.67	0.87
360	0.93	0.90	0.79	0.87	0.81	0.84	0.82	0.76	0.71	0.72
350	0.66	0.68	0.69	0.73	0.82	0.69	0.73	0.70	0.59	0.73
340	0.71	0.77	0.72	0.74	0.69	0.61	0.78	0.84	0.84	0.60
330	0.68	0.67	0.72	0.68	0.54	0.70	0.38	0.54	0.64	0.85
320	0.86	0.83	0.79	0.93	0.98	0.93	0.94	0.90	0.93	0.88
310	0.82	0.69	0.72	0.87	0.86	0.89	0.97	0.78	0.88	0.84
300	0.92	0.88	0.93	0.95	0.74	0.84	0.78	0.72	0.81	0.73
290	0.82	0.86	0.69	0.76	0.82	0.73	0.70	0.85	0.83	0.62
280	0.70	0.81	0.66	0.84	0.87	0.72	0.72	0.72	0.65	0.70
270	0.65	0.70	0.84	0.77	0.70	0.74	0.72	0.68	0.67	0.86
260	0.82	0.74	0.64	0.64	0.78	0.69	0.69	0.71	0.72	......

Sequoia record: Group of 1915; 11 trees.

B. C.	0	9	8	7	6	5	4	3	2	1
280	......	......	......	......	......	......	3.82	4.38	3.78	2.87
270	2.96	2.59	2.73	2.55	0.84	2.85	2.27	2.70	2.76	3.56
260	3.16	3.08	3.71	2.92	2.54	2.41	2.20	2.16	2.37	2.73
250	2.66	2.47	2.13	2.32	1.67	1.29	0.87	1.42	1.72	1.83
240	1.53	1.52	1.61	1.15	1.09	0.63	1.19	1.19	1.51	1.05
230	1.30	1.22	1.29	1.22	1.12	1.48	1.55	1.40	1.06	1.35
220	1.55	1.52	1.64	1.75	1.26	1.21	1.25	1.65	2.06	1.77
210	2.33	2.11	2.02	2.71	2.88	2.40	2.58	2.23	1.82	2.16
200	2.19	2.23	2.40	2.61	2.35	2.38	2.62	2.72	2.02	2.28
190	3.10	2.85	2.80	3.15	3.01	2.98	2.17	2.48	1.92	1.86
180	2.33	2.78	2.44	2.20	2.50	2.59	2.35	2.40	2.11	1.97
170	1.77	2.00	1.52	2.51	2.96	2.89	1.89	1.93	1.47	1.76
160	1.20	1.10	1.42	1.77	2.02	2.00	2.20	2.14	1.90	2.87
150	2.26	2.28	2.74	2.58	2.60	2.36	2.34	2.06	2.66	1.70
140	2.78	2.54	2.25	2.42	2.28	2.07	2.20	2.34	2.36	2.52
130	2.00	2.01	2.18	2.44	2.04	2.18	1.87	2.00	2.23	2.23
120	2.20	2.48	2.66	2.34	2.16	2.29	2.54	2.33	2.15	2.28
110	2.64	2.66	2.33	2.24	2.85	2.55	2.44	2.16	2.21	1.91
100	1.62	2.08	2.22	1.96	1.85	1.75	1.65	1.85	1.90	1.80

Sequoia record: Group of 1915; 11 trees—continued.

B. C.	0	9	8	7	6	5	4	3	2	1
90	1.74	1.80	1.89	1.68	1.68	1.56	1.80	1.37	1.92	2.27
80	2.34	2.16	2.25	2.17	2.00	2.63	2.16	2.08	2.16	2.27
70	2.26	1.85	2.20	2.13	2.18	1.87	2.43	2.22	1.64	1.70
60	2.22	2.35	2.48	2.52	2.00	1.90	1.89	1.58	1.54	1.85
50	1.75	1.58	1.42	1.31	1.24	1.60	1.81	1.78	1.72	1.66
40	1.75	1.64	1.59	1.59	1.70	1.68	1.57	1.35	1.53	2.14
30	1.86	1.71	1.50	1.62	1.50	1.54	1.34	1.62	1.79	1.38
20	1.78	1.38	1.46	1.71	1.44	1.70	1.23	1.23	1.04	1.24
10	1.44	0.98	1.38	1.52	1.44	1.42	1.40	1.29	1.56	1.60

A. D.	0	1	2	3	4	5	6	7	8	9
0	1.68	1.58	1.70	1.93	1.83	1.56	1.67	1.24	1.39	1.65
10	1.92	1.60	1.30	1.21	1.33	0.89	1.24	1.72	1.96	1.58
20	1.57	1.68	1.74	1.80	1.71	1.82	1.83	1.78	2.01	1.94
30	1.87	1.76	1.76	1.74	1.80	2.06	2.39	1.74	1.69	2.00
40	2.11	1.75	1.83	1.64	1.88	2.06	2.00	1.72	1.60	1.61
50	1.44	1.27	1.19	1.40	1.44	1.45	0.98	1.00	1.42	1.54
60	1.21	1.17	1.26	1.09	1.03	1.23	1.38	1.31	1.36	0.86
70	1.42	1.20	1.49	1.55	1.41	1.33	1.25	1.21	1.27	1.32
80	1.28	1.59	1.52	1.48	1.54	1.77	1.48	1.38	1.50	1.44
90	1.50	1.42	1.46	1.35	1.15	1.15	1.25	1.33	1.06	1.23
100	0.86	1.25	1.11	1.18	1.17	1.14	0.80	1.17	0.99	0.44
110	1.04	1.28	1.82	1.85	1.26	1.16	1.26	1.38	1.31	1.38
120	1.13	1.07	1.20	1.06	0.99	1.05	1.05	1.06	0.92	1.13
130	0.98	0.96	0.92	0.90	0.92	0.93	1.19	1.14	1.12	1.07
140	1.02	1.00	0.93	1.10	1.10	1.10	1.12	1.14	1.27	1.12
150	1.01	0.98	0.59	0.99	1.16	0.92	1.19	0.93	1.08	1.10
160	0.93	0.98	1.04	1.24	1.02	1.04	1.06	0.79	0.54	0.55
170	0.81	0.99	0.79	0.74	1.00	1.20	1.01	1.17	0.87	0.91
180	0.98	0.86	1.15	1.02	1.00	1.13	1.12	1.16	0.98	0.49
190	0.87	1.29	1.52	1.59	1.47	1.40	1.35	1.42	1.28	1.39
200	1.25	1.42	1.37	1.58	1.58	1.81	1.68	1.19	1.18	1.30
210	1.40	1.40	1.28	1.11	1.06	1.07	1.30	1.06	1.98	0.94
220	0.82	1.10	1.09	1.04	1.10	0.90	0.77	1.00	1.15	0.92
230	0.93	0.94	1.10	1.09	1.03	1.06	0.66	0.99	0.98	0.75
240	0.98	1.07	0.88	0.91	1.02	0.94	1.06	1.04	0.98	0.97
250	1.00	0.89	0.95	0.82	0.96	0.90	0.74	0.81	0.80	0.91
260	1.02	1.00	0.92	0.97	1.01	0.95	0.89	1.02	1.03	1.01
270	0.84	0.61	0.92	0.92	0.60	0.90	0.84	0.96	0.91	0.88
280	1.04	0.85	0.95	0.98	0.94	0.88	0.98	0.96	0.92	0.99
290	1.08	1.10	0.74	0.87	0.85	1.14	0.96	0.84	1.14	0.98
300	0.91	1.08	1.00	1.03	0.96	0.56	0.60	0.76	0.87	0.96
310	0.98	1.09	0.92	0.60	1.02	0.89	0.85	0.91	1.04	0.85
320	0.92	0.82	0.99	0.86	0.89	0.87	0.83	0.85	1.04	0.78
330	0.78	0.84	0.78	0.46	0.68	0.88	0.76	0.82	0.80	0.68
340	0.62	0.75	0.91	0.81	0.54	0.78	0.74	0.82	0.97	0.68
350	1.04	0.86	0.90	0.78	0.93	0.88	0.88	0.72	0.98	0.89
360	0.91	0.80	1.00	1.05	1.21	1.12	1.35	1.32	1.07	0.74
370	0.81	1.08	1.23	1.47	1.73	1.79	1.56	1.08	1.34	1.68
380	1.83	1.89	1.95	1.82	1.79	1.75	1.13	1.30	1.60	1.62
390	1.59	1.64	1.54	1.63	1.66	1.60	1.40	1.44	1.26	1.31
400	1.79	1.92	1.88	1.53	1.43	1.76	1.77	1.62	1.61	1.68
410	1.68	1.83	1.73	1.68	1.52	1.81	2.03	1.91	1.90	2.09
420	2.19	1.92	1.92	1.82	1.64	1.76	2.14	2.34	2.19	2.12
430	2.07	1.92	1.79	1.66	1.78	1.66	1.90	1.80	1.59	1.62
440	1.68	1.89	1.27	1.55	1.58	1.89	1.69	1.48	1.20	1.39
450	1.37	1.24	1.18	1.21	1.28	1.34	1.59	1.60	1.44	1.36
460	1.38	1.32	1.26	1.35	1.30	1.39	1.21	1.29	1.29	1.30
470	1.50	1.47	1.29	1.41	1.23	1.56	1.52	1.27	1.48	1.65
480	1.57	1.61	1.67	1.73	1.76	1.66	1.70	1.68	1.54	1.76

Sequoia record: Group of 1915; 11 trees—continued.

A. D.	0	1	2	3	4	5	6	7	8	9
490	1.48	1.47	1.60	1.52	1.76	1.92	1.94	1.51	1.50	1.88
500	1.55	1.48	1.44	1.61	1.85	1.70	1.52	1.31	1.47	1.62
510	1.61	1.92	1.39	1.27	1.19	1.26	1.39	1.07	0.68	1.10
520	0.94	1.33	1.45	1.14	1.02	1.15	1.08	1.11	1.24	1.29
530	1.14	1.27	1.24	1.26	1.18	1.27	1.30	1.33	1.21	0.78
540	0.94	0.99	0.86	0.91	0.96	1.19	1.15	1.16	1.08	0.98
550	0.97	1.03	0.72	0.48	0.45	0.82	1.09	0.79	1.07	1.34
560	1.61	1.23	1.45	1.21	1.20	1.07	1.13	1.27	1.08	1.14
570	0.84	0.98	1.03	1.08	1.16	1.04	0.99	0.92	0.94	1.09
580	0.94	1.04	0.78	0.99	0.99	0.98	0.77	1.29	1.16	1.12
590	1.16	0.95	1.22	1.09	1.06	1.10	1.27	1.00	0.98	0.95
600	1.17	1.19	0.97	1.29	1.22	1.27	1.12	1.06	1.45	1.30
610	1.36	1.40	1.02	1.28	1.54	1.52	1.61	1.74	1.67	1.72
620	1.28	1.46	1.62	1.71	1.35	1.30	1.23	1.54	1.53	1.20
630	1.28	1.24	1.28	1.24	1.47	1.35	1.36	1.28	1.26	1.14
640	0.84	1.10	1.16	1.45	1.64	1.43	1.30	1.36	1.50	1.62
650	1.22	1.07	1.38	1.52	1.49	1.57	1.31	1.27	1.46	1.03
660	1.23	1.21	1.57	1.78	1.37	1.51	1.41	1.50	1.52	1.32
670	1.54	1.39	1.49	1.44	1.49	1.51	1.21	1.10	1.41	1.07
680	1.54	1.55	1.53	1.14	1.20	1.19	1.25	1.35	1.28	1.21
690	1.33	1.15	1.53	1.67	1.49	1.36	1.17	1.22	1.38	0.55
700	1.20	1.58	1.37	1.41	1.50	1.47	1.60	1.01	1.29	1.30
710	1.30	1.34	1.22	1.16	1.04	0.93	1.15	1.23	1.00	0.74
720	1.08	1.18	0.97	1.09	0.96	1.25	1.19	1.08	0.80	1.14
730	1.27	1.24	1.33	1.49	1.32	1.27	1.33	1.59	1.34	1.10
740	1.25	1.22	0.84	1.41	1.31	1.51	1.13	1.22	1.08	1.24
750	1.16	0.87	1.04	0.96	0.88	0.90	1.04	1.08	1.19	1.20
760	0.88	0.96	0.56	0.82	0.75	1.00	0.91	0.95	0.94	1.10
770	1.16	1.39	1.48	1.29	1.20	1.50	1.34	1.39	1.47	1.17
780	1.62	1.12	1.04	1.23	1.36	1.17	0.96	1.11	0.87	1.10
790	1.40	1.13	1.16	1.12	0.99	1.18	1.39	0.75	1.17	1.20
800	1.19	1.11	1.18	1.19	0.88	1.01	1.42	1.04	1.11	0.73
810	0.99	1.22	1.23	1.15	1.24	1.28	1.26	1.17	1.02	0.83
820	1.10	1.17	1.32	0.89	1.09	1.08	1.25	1.30	1.29	1.16
830	1.10	1.24	1.38	1.07	1.18	1.26	1.25	1.32	1.27	1.13
840	0.99	1.10	1.10	1.35	1.19	0.97	1.21	0.92	1.23	1.23
850	1.15	1.16	1.16	1.22	1.09	0.99	1.06	1.01	1.13	1.14
860	1.19	1.00	1.04	1.04	1.12	0.67	1.23	1.20	0.63	1.14
870	1.32	1.08	1.03	0.97	1.18	1.10	0.98	1.12	1.17	1.18
880	1.24	1.35	1.41	1.13	1.22	1.53	1.42	1.08	1.29	1.15
890	1.00	1.05	1.33	1.33	1.10	1.13	1.24	1.31	1.11	1.21
900	1.03	1.25	1.10	1.07	1.12	1.13	1.03	1.01	1.10	1.00
910	1.06	1.15	1.10	0.84	1.17	0.97	1.15	1.28	1.06	1.09
920	1.20	1.08	1.24	1.05	0.87	1.04	1.09	1.09	1.03	0.90
930	0.74	0.98	1.00	0.72	1.05	1.01	1.02	1.29	1.05	1.21
940	1.24	1.20	1.15	0.99	0.91	1.06	1.19	1.28	1.01	1.01
950	1.20	1.09	0.94	0.97	0.47	0.91	1.08	0.71	0.89	1.07
960	1.22	0.87	0.92	1.15	1.06	1.07	0.98	1.16	1.33	1.28
970	1.50	1.14	1.09	1.22	1.15	1.01	1.08	1.14	1.00	0.82
980	0.62	0.76	0.92	0.96	1.19	1.36	1.15	1.24	1.21	1.33
990	1.28	1.41	1.36	1.40	1.17	1.04	1.04	1.39	1.42	1.24
1000	1.30	1.44	1.45	1.55	1.35	1.20	1.46	1.36	1.35	1.31
1010	1.11	1.34	1.22	1.20	1.20	1.37	1.58	1.54	1.36	1.60
1020	1.49	1.38	1.38	1.56	1.56	1.10	1.31	1.32	1.16	1.13
1030	1.14	1.08	0.98	1.10	1.19	1.08	1.12	1.22	1.21	1.06
1040	1.00	1.23	1.28	1.03	0.99	1.20	0.99	0.88	0.93	0.95
1050	1.02	1.02	0.76	0.70	0.79	0.84	0.94	0.81	0.82	0.58
1060	0.58	0.91	0.89	0.92	1.19	1.17	1.08	1.25	1.36	1.13
1070	0.90	1.24	0.99	1.08	1.21	1.32	1.30	1.15	1.08	1.16

Sequoia record: Group of 1915; 11 trees—continued.

A. D.	0	1	2	3	4	5	6	7	8	9
1080	1.17	1.08	0.71	1.11	1.09	1.10	0.95	1.14	1.05	1.07
1090	0.88	0.89	0.82	0.64	0.99	1.13	0.93	1.06	0.76	0.83
1100	1.11	1.04	1.05	0.92	0.90	1.00	0.87	0.84	0.86	1.05
1110	0.93	0.96	0.96	1.01	1.00	1.10	1.24	1.17	1.24	1.07
1120	1.18	1.17	1.11	0.93	1.02	1.19	0.57	0.70	0.99	1.00
1130	1.00	0.88	0.90	0.91	0.90	0.97	1.11	0.96	0.95	0.94
1140	0.92	0.92	1.08	0.96	0.89	0.83	0.89	0.97	0.89	1.07
1150	0.88	0.76	0.52	0.63	0.83	0.84	0.34	0.65	0.85	0.99
1160	1.00	0.93	0.80	1.06	0.87	1.00	1.02	1.05	0.85	1.12
1170	0.84	0.81	0.87	0.82	0.91	0.63	0.72	0.60	0.80	0.89
1180	0.88	1.06	0.92	0.71	0.99	0.87	1.06	0.93	1.12	1.10
1190	1.00	1.00	0.98	0.90	1.04	1.06	0.91	0.98	0.94	1.04
1200	1.09	1.08	0.96	0.94	1.00	1.04	0.79	0.85	0.82	1.02
1210	0.98	0.86	0.93	0.92	1.06	0.86	0.96	0.84	0.74	1.00
1220	0.93	0.83	0.82	0.87	0.87	0.91	0.82	0.73	0.91	0.97
1230	0.95	0.73	0.83	0.91	0.80	0.78	0.64	0.62	0.78	0.79
1240	0.84	0.86	0.76	0.74	0.77	0.64	0.93	0.87	1.04	0.80
1250	0.57	0.70	0.84	0.84	0.70	0.71	0.99	0.88	0.97	1.00
1260	0.97	0.85	0.80	0.57	0.54	0.85	0.92	0.86	0.79	0.70
1270	0.97	0.99	0.96	0.81	1.06	1.05	0.87	0.97	1.10	0.72
1280	0.83	0.91	0.94	1.00	0.74	0.58	0.86	0.94	0.85	0.87
1290	1.00	1.00	0.71	0.85	0.98	0.74	0.48	0.85	0.78	1.01
1300	0.91	0.97	1.03	1.01	1.17	1.20	1.21	1.27	1.15	0.95
1310	1.17	1.06	1.22	1.28	1.14	1.24	0.85	1.03	1.20	1.20
1320	1.03	1.07	1.12	1.17	1.04	0.92	1.24	1.34	1.19	1.18
1330	1.35	1.31	1.02	1.05	1.16	0.90	1.14	1.20	1.23	1.14
1340	1.25	1.26	1.16	1.09	1.15	1.17	1.11	1.06	1.01	1.26
1350	1.03	0.93	0.66	0.97	0.96	1.10	1.27	1.09	0.96	1.03
1360	1.05	0.97	1.10	1.21	1.15	0.83	1.06	1.22	1.20	1.15
1370	1.06	1.05	1.15	1.14	1.05	1.01	0.95	0.76	0.99	1.04
1380	1.21	1.21	1.03	1.09	1.04	1.09	1.04	0.97	1.00	1.13
1390	0.81	0.87	0.98	1.03	1.01	0.87	0.81	0.91	0.90	0.92
1400	0.84	0.86	0.74	0.80	0.86	0.88	0.88	0.84	0.76	0.91
1410	0.72	0.89	0.94	0.75	1.05	1.10	1.11	1.10	1.11	1.05
1420	1.27	1.02	1.25	1.16	1.13	0.92	0.70	0.90	0.85	0.90
1430	0.83	0.81	0.83	0.85	0.81	0.78	0.84	0.80	0.80	0.79
1440	0.80	0.81	0.74	0.72	0.75	0.88	0.79	0.74	0.78	0.71
1450	0.77	0.75	0.66	0.74	0.71	0.77	0.73	0.68	0.75	0.78
1460	0.77	0.79	0.81	0.76	0.70	0.74	0.73	0.84	0.66	0.77
1470	0.91	0.76	0.72	0.61	0.73	0.71	0.68	0.86	0.87	0.57
1480	0.77	0.86	0.88	0.94	1.00	0.78	0.88	0.82	0.94	0.94
1490	0.88	0.87	0.84	0.86	0.88	1.00	0.96	0.82	0.89	0.66
1500	0.63	0.85	1.06	0.94	0.94	0.95	1.00	0.98	1.05	1.07
1510	0.85	0.86	1.04	1.06	0.97	0.84	0.82	0.93	0.66	0.91
1520	0.94	0.97	0.94	0.99	1.09	1.11	1.05	0.95	1.03	0.60
1530	0.90	1.06	0.64	0.70	1.03	1.03	0.87	0.89	0.96	1.12
1540	0.88	0.68	0.80	0.88	0.94	0.87	0.96	1.04	0.73	0.94
1550	0.84	0.97	0.92	0.95	0.77	0.82	0.88	0.85	0.89	0.82
1560	0.87	0.85	0.77	0.78	0.90	0.87	0.76	0.81	0.89	0.78
1570	0.82	0.48	0.70	0.80	0.77	0.76	0.68	0.78	0.70	0.50
1580	0.12	0.53	0.66	0.78	0.68	0.66	0.72	0.80	0.75	0.87
1590	0.68	0.75	0.77	0.81	0.76	0.76	0.80	0.81	0.79	0.75
1600	0.69	0.88	0.89	0.85	0.98	0.99	0.87	0.81	0.88	0.88
1610	0.94	0.97	0.86	0.67	0.86	0.92	0.89	0.94	0.84	0.79
1620	0.86	0.90	0.77	0.96	1.01	1.04	0.90	0.89	0.97	0.89
1630	0.91	0.78	0.45	0.63	0.75	0.87	0.93	0.66	0.81	0.92
1640	1.02	1.01	0.96	0.95	1.00	1.00	0.92	0.87	0.91	0.94
1650	0.77	0.86	0.82	0.74	0.52	0.58	0.78	0.75	0.84	0.74
1660	0.83	0.83	0.79	0.81	0.79	0.85	0.86	0.67	0.82	0.70

Sequoia record: Group of 1915; 11 trees—continued.

A. D.	0	1	2	3	4	5	6	7	8	9
1670	0.68	0.73	0.81	0.86	0.89	0.91	0.77	1.03	0.89	0.85
1680	0.94	0.78	0.73	0.82	0.76	0.83	0.71	0.80	0.78	0.73
1690	0.72	0.54	0.78	0.76	0.79	0.79	0.73	0.79	0.65	0.67
1700	0.64	0.63	0.90	0.65	0.72	0.89	0.64	0.72	0.80	0.95
1710	0.74	0.67	0.68	0.76	0.73	0.70	0.84	0.88	0.74	0.71
1720	0.86	0.70	0.70	0.83	0.82	0.93	0.91	0.84	0.83	0.48
1730	0.85	0.89	0.97	0.95	1.01	0.99	0.86	0.91	0.98	0.73
1740	0.92	1.04	0.96	0.96	0.96	1.10	0.90	1.01	0.83	0.88
1750	1.11	0.99	0.96	0.94	0.91	0.85	0.69	0.79	0.93	1.00
1760	1.06	1.13	1.01	1.08	1.05	0.85	1.14	1.21	1.25	1.05
1770	1.10	1.16	1.16	1.08	1.17	1.06	0.85	0.48	0.73	0.90
1780	0.97	0.87	0.52	0.67	0.93	0.98	1.05	1.00	0.82	0.95
1790	1.04	1.03	1.07	0.95	0.83	0.57	0.63	1.12	1.14	1.19
1800	1.06	1.13	1.09	1.07	0.96	0.99	0.93	0.91	0.83	0.81
1810	0.84	0.99	0.79	0.88	1.03	0.92	0.99	1.03	0.78	0.88
1820	0.88	0.84	0.74	0.75	0.71	0.97	0.94	0.78	0.77	0.55
1830	0.77	0.89	0.98	0.83	0.81	0.80	0.86	0.87	0.90	0.81
1840	0.77	0.52	0.73	0.69	0.83	0.95	0.90	0.97	0.89	0.95
1850	0.92	0.80	0.96	1.03	0.82	0.85	0.79	0.91	0.69	0.74
1860	0.91	0.88	0.86	0.84	0.61	0.76	0.87	0.91	0.88	0.80
1870	0.78	0.80	0.83	0.87	0.79	0.86	0.99	0.80	1.11	0.99
1880	1.08	1.23	1.01	1.17	1.19	1.14	1.10	0.99	1.12	1.16
1890	1.20	1.12	0.94	1.11	1.10	1.11	1.09	1.10	0.84	0.90
1900	1.11	0.98	0.76	0.82	0.96	0.91	0.90	0.93	0.82	0.89
1910	0.78	0.90	0.87	0.83	0.85	......	......	......	......	......

NOTE.—The dates in table 4 on page 45 should be altered by one year to agree with those in table 5 on page 52.

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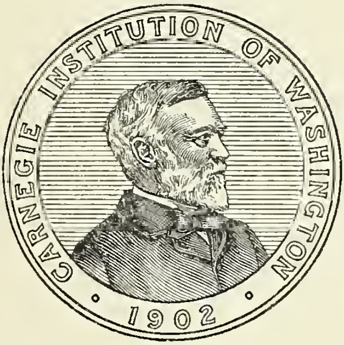

1928

CLIMATIC CYCLES AND TREE-GROWTH

VOLUME II

A STUDY OF THE ANNUAL RINGS OF TREES IN RELATION TO CLIMATE AND SOLAR ACTIVITY

BY

A. E. DOUGLASS

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With nine plates and nineteen text figures

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VOLUME II

I. INTRODUCTION

In a dry region the dominating physical factor in tree-growth is moisture. It is impossible for anyone to realize how vital it is without actual residence—a mere trip through a desert is far from sufficient, for it lacks the time element. One must live in it by night and by day, in rainy and in dry season, in drought and in wet cycle. One must see the burning sun, the sparse shrubs, the clear skies, the striking colors of earth, rock, and sky, without the green of vegetation, followed by the strong primitive atmospheric colors when the sun is just below the horizon; he must see the round green cedars and the ever watchful isolated pines of higher elevations; he must see green valley bottoms and herds escaping from sight through deep range grass at one time, and later on he must travel through cactus wastes and dead cattle lying beside dried-up water-holes. And all this must be lived with to afford full realization. The visitor from wet climates does not sense it all for the first year or two, for day by day he unconsciously expects a change, as has always happened in his previous experience. But after a year or more he is able to realize the excessive value of moisture and even to recognize the evidence of climatic changes.

This was the approach in the present study of climate and trees. Many investigators have come to the study of growth variations from other viewpoints. For example, a large number think of them in terms of pests, for economic necessity has demanded their study, especially in wet climates, where timber is abundant and they are nature's agents for maintaining an equilibrium. It is true that the relation of the abundance of animal life, even pests, to climatic conditions is receiving more and more consideration, but the supreme rôle of rain in a dry climate needs to be a matter of constant experience in order to bring appreciation of the relation of tree-growth to moisture in the Southwest.

AFFILIATIONS

At the outset this work was recognized as on the borderland between astronomy, meteorology, and botany, and as needing help and information from each with some expectation of ultimate return. To some degree this return is realized in the present volume, which gives for the astronomers some evidence of a real history of solar changes for many centuries, for the meteorologists certain drought conditions and climatic changes over a similar length of time, and for the botanists an opportunity for learning how vegetation reacts to certain phases of its environment. In addition, various problems of dating, such as the chronology of the prehistoric ruins of the Southwest, have received a new approach, but solar and climatic cycles with an ultimate view to seasonal prediction have continued the central theme.

Prediction possibility has been one of the great incentives to recent work upon tree-rings. There seem to be two approaches to long-range forecasting. One is by direct tracing of the physical causes and the other is by learning the history of past changes and working out empirical methods. Each needs the other; so the climatic history written in trees is doubly useful, for it may of itself give means of foretelling the future, if such can be found, and, on the other hand, if the physical causation is traced first, the derived line of causes must agree with and explain this known history in trees. Thus prediction will gain at once greater reliability. The last chapter in the book deals with the various climatic cycles found in trees.

The effort to find a basis of seasonal prediction is the modern phase of an age-old problem. In our day of newspapers, calendars, and clocks it is hard to realize that at the beginning of prehistoric agriculture farmers knew little of the time of day or the time of year except as signs in the heavens told it to the rare man who had learned the language of the sky. We are now in the same stage of ignorance regarding yet longer cycles and hope to find our time in relation to them so that we may know better when and what to produce each season for modern needs.

DEVELOPMENT

With a conviction of the climatic value of tree-ring studies, one can see two general lines of development, roughly described as extension in space about the world at the present time and extension in time to past eras. The former has economic and scientific value, because, in this way, climatic variations in different hemispheres, continents, and latitudes may, within limits, be studied, in spite of absence of formal instrumental records; so also the effects of mountain ranges, continental contours, different orientation of exposure, and the reaction of vegetation under different conditions. A beginning is made in this volume along these lines. A set of yellow pine ring records has been obtained from the Western States, and especially the Southwest, by which a large area can be reviewed and a first estimate made of effects such as those just mentioned.

Similar information regarding past climates is contained in fossil trees. Without knowing exact dates, we can learn something about the climatic and solar changes in various geologic periods, Tertiary, Pleistocene, Prehistoric, and Protohistoric. The methods and instruments developed in this research give us an improved approach to various types of geologic material besides fossil woods. Chief among these are the clay layers of de Geer and Antevs, dealing with the retreat of the ice-sheet, the andesite laminations of Udden in Texas, and the stalagmite deposits of Allison. This geologic material, with much more that will come to light, will not be included in the present volume, but will be reserved for future discussion.

One can see that in all this we are measuring the lapse of time by means of a slow-geared clock within the trees. For this study the name "dendro-chronology" has been suggested, or "tree-time." This expression covers all the dating and historic problems referred to in the following chapters, as well as the study of cyclic variations and the distribution of climatic conditions.

COÖPERATION

But with this development there is added need of information from other sciences. The relationship of solar activity to weather is a part of a rather specialized department of astronomical science called astrophysics. There is help which one needs from that science, but which one can not yet obtain; for example, the hourly variations in the solar constant. One would like to know whether the relative rate of rotation and the relative temperatures of different solar latitudes vary in terms of the 11-year sunspot period. These questions have to do with some of the theories proposed in attempting to explain the sunspot periodicity. We do not know the cause of the 11-year sunspot period. Here, then, is work for the astronomers. Climate is a part of meteorology, and the data which we use are obtained largely from the Weather Bureau. The observing stations are usually located in cities, and therefore we can not get data from proper places in the Sierra Nevada Mountains of California, where the giant sequoia lives. Considering that this big tree gives us the longest uninterrupted series of climatic effects whose dates are accurately known, which we have so far obtained from any source, it must be greatly regretted that we have no long modern records by which to interpret the writing in those wonderful trees. So far as I am aware, only one attempt is now being made to get complete records for the future.*

From the botanists and ecologists we need to know the exact time of ring formation, the ability of the tree to conserve moisture against the day of drought, the soil-moisture gradients at different months, the different action of the tree in putting on a different color of wood in the spring and autumn growth.

In dating problems, this study has developed another important contact. The rings in the beams of ancient ruins tell a story of the time of building, both as to its climate and the number of years involved and the order of building, perhaps ultimately the date of building. All this is anthropology, and much data from the archæologists will help in identifying the rings in beams and supply valuable climatic records of long-past times.

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*Col. John R. White, in Sequoia National Park.

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PREVIOUS WORK

The first publication by the author was in 1909, in the Monthly Weather Review. This was followed by other articles until the whole was summarized in 1919 in a volume with the same title as the present one and published under the same auspices. At that time identification and measurement had been made of about 75,000 rings in some 230 different trees from the States of Oregon, California, Arizona, Colorado, and Vermont, as well as from England, Norway, Sweden, Germany, and Bohemia (near Pilsen). That volume dealt with studies upon the yellow pine about Flagstaff, Arizona, climatic conditions there, the yearly identity of rings, cross-identification, time of year of ring formation, number of trees necessary, the actual collection of yellow and Scotch pine and sequoia samples, methods of curve production, correlation with rainfall and with solar activity, and cycles and methods of determining them. The present book opens with the development of technique in collecting and treating specimens.

II. TREE SELECTION

Rings of trees have told many stories of the past. By their mere enumeration the historian has built up our realization of great events in human progress; by more careful counting the forester has discovered the dates of ancient destructive fires; by changes in the rings ecologists have determined historic changes in lakes and rivers and settled questions of legal ownership. The present study of climate and solar activity uses the accurate dating and width of rings over wide geographical areas and into times long past for several purposes, but chiefly to derive an understanding of that immensely complex process by which climatic forces reach the earth and distribute themselves about it. This, it is hoped, will eventually lead to safe long-range prediction of climatic conditions. In the present approach to the subject, the recent development of technique is given first, and this chapter deals with the selection of trees for climatic study.

SPECIES

Pines—The western yellow pine is perhaps the best tree for climatic studies, on account of its precision and length of record and its wide distribution. It is normally a dry-climate tree and does well in a sandy soil, for its thick bark prevents evaporation from the trunk and thus enables it to live when other trees could not survive. Thus it endures relatively trying conditions and has little competing vegetation, so that the Arizona forest is said to be the largest "pure" stand in the country. It can be injured by too much moisture in the soil, and draining then improves it. Its age is very favorable, reaching over 500 years. It is commonly free from burns and defects and its rings are very readable. The immense area over which the yellow pine grows adds to its value in this study, as its use avoids the complexities arising from the use of different species. For all these reasons it is considered the standard tree.

The Scotch pine of north Europe is very similar, but not usually so large. However, this is because the European regions have been cut over so much that very old trees are rare. The white pine in the Appalachian Mountains cross-identifies very well. The pines in eastern Massachusetts are less satisfactory, probably because the region is too much cultivated. Very old hemlocks in the Green Mountains of Vermont have rings extraordinarily like those of the western yellow pine and almost as perfect in cross-identification.

White pines in the Yellowstone are good, and a few white or limber pines near Flagstaff give records that are readable, but the locations in which they grow are so rugged and variable that a complete test has not been made of them. The foxtail pine at high altitudes sometimes reaches a great age, but its rings are more complacent than those of the yellow pine. It reminds one of a cedar.

Sugar pine—Sugar pines are fine, large trees, but the rings are large and the age is often disappointing. The distribution is much more limited than the yellow pine; from which one assumes that it will not stand so great a variation of moisture. Ring records of this species on Mount Wilson resemble very closely similar records from the adjacent yellow pines. Like the Douglas fir, it is a good occasional substitute for the yellow pine, but is far from its equal as a standard tree in southwestern climatic study. Substitute trees have given so many cases of satisfactory records that one feels it always worth while to use some other tree than the yellow pine where such standard trees are scarce.

Douglas fir (spruce)—In the Arizona Mountains this tree borders the pine belt on the upper, which is the colder and more rainy side. It mixes with the yellow pine to a small degree and is the first choice as substitute when the pines are infrequent in any site. The trees, even if bigger, are apt to be younger, with larger growth each year. The rings are usually well marked and free from errors and cross-identify perfectly with neighboring yellow pines. It is somewhat apt to exaggerate climatic influences.

Other spruces—The Sitka spruce of our northwest coast (tested in Oregon and Washington) has heavy, emphatic rings of a complacent sort and so far has not seemed a desirable tree. It grows to exceedingly large size. A fine specimen some 9 feet through, in the American Museum in New York, gives a good idea of what it is. This particular specimen exhibits some very unusual spiral gross-rings whose origin it would be interesting to determine. This spruce grows at low, well-watered levels near the coast, and so its value as a climatic record is probably low.

The Engelmann spruce of high altitudes is even less valuable in this respect. It grows at elevations over 8,000 feet at Pike's Peak and at 10,000 on the San Francisco Peaks (Arizona). Its rings have very little variation and do not cross-identify with neighboring pines and Douglas firs. Owing to these characteristics it has practically no value as a climatic record.

The European spruce, *Picea excelsa*, is much better. While more complacent than the very satisfactory Scotch pine there, it does show good ring variations which can be dated and in one or two special cases give a remarkable record of solar variations. Such is No. S 14 from southern Sweden, whose photograph is given here (see Plate 9) because it did not come in time for insertion in the first volume. Its curve of growth was given in Volume I, page 75, figure 22. It is therefore unusual and interesting.

Sequoias—In this review of western trees the mountain sequoia (*Sequoia gigantea*) easily takes a leading part in company with the yellow pine, for besides its great age it has a fundamental feature of greatest importance, namely, cross-identification over large areas. In this character we recognize climatic influences. The ring-growth in the big sequoia is not so sensitive as in the yellow pine, and perhaps any individual tree is a little less certain to identify with its neighbors, but yet cross-identification is very sure in that species and extends through all the mountain sequoia groves from Calaveras on the north to Springville on the south, 200 miles. The southern groves, which yield the best results, give a record obviously similar to that of the yellow pines in neighboring locations. It is true that the sequoia needs a large moisture supply, probably more than it usually gets, but its location is so high on the mountains that the winters completely interrupt the growth and therefore make the record in the rings very reliable as to its annual character. The great age of this tree gives it a second fundamental value. It is astonishing, for example, to find over considerable areas similar identifiable rings near 1,000 B. C. Further study upon the sequoia will improve our knowledge of the normal growth-curve in relation to age, so that we can by extrapolation tell with some precision what the climate was 3,000 years ago. This requires many corrections, such as that for flare of the base, for slanting rings, and for the indentations of the trunk which come from root relationship. All these factors differ so much in individual trees that it would seem profitable to study each tree specially, and in recent collecting I have made notes about every stump and have distributed the ages more carefully. (See Huntington, 1914.)

Coast redwood—The coast redwood (*Sequoia sempervirens*) has been a disappointment, because after most careful tests it has failed entirely to show cross-identification. This is undoubtedly due to its climatic environment. Various attempts to make use of this tree are described below (Chapter VI).

Junipers—The junipers and cedars are important in this review, because in Arizona mountains they border the yellow pines on the lower and therefore the warmer and drier side. As one ascends from the desert to the forest areas, the first dark-green rounded trees are the junipers of several different species. The growth of the juniper is slow and the rings are often attractive, but for actual use disappointing. One species branches at the ground and so seems impossible; another has deep vertical indentations in the trunk, with erratic rings. The growth can rarely be traced from lobe to lobe of a cross-section. Often the rings condense so that identity is hopelessly lost.* The more promising species is the pachyphlœa or alligator-bark juniper, which grows close to or in the pine belt. Its rings are apt to be complacent, with considerable difference in mean size due to locality. From the average rate of growth of junipers measured near Cibecue, 500 to 700 years would seem to be the usual maximum age of this tree.

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* Some successful work has recently been done on the junipers.

This species has one idiosyncrasy which often rules out an attractive tree. A vertical half may die and the other half live. This may happen to the trunk and follow up some of the larger branches nearly to the top of the tree. Close to Elden Spring at Flagstaff is a juniper of this sort which is 4 feet through east and west and is still growing actively in those directions, but north and south it is only a foot through and completely dead. The alligator-bark juniper is more promising than the other species and may become a valuable tree on more complete investigation.

The cedars are somewhat like the last-mentioned juniper. They are rather complacent, but do show some variations. The west coast cedars take a good deal of water-supply. Some extremely large ones are occasionally found, but they have not seemed promising. The rings are generally larger than the sequoia rings and for the same size the trees are not so old. Many cedars growing in the vicinity of the sequoias have been examined and the ring record is considered below the big tree record in quality.

Oak and other hardwoods—The oak is less generally distributed in the Southwest than the yellow pine, but there are large and important areas over which it is the available tree. Various samples collected seem very promising, but it has not been available extensively in the form of stumps and it is too hard to bore, so no final tests can be reported here. Kapteyn's first work in the Rhine Valley was on oaks, and in the last few years (1921) Professor William J. Robbins, of Columbia, Missouri, has traced a fine relationship between oaks and spring rainfall. This tree was used in the Swiss lake dwellings, and fossil oaks are very common, showing some of the best ring records to be found in museum specimens. Undoubtedly it is a valuable tree.

Beech rings in northwestern Pennsylvania show good variations and seem very promising. This is well to keep in mind, because there are great beech forests in South America whose rings may contain important climatic information.

Tropical hardwoods have been examined in museums in large numbers. The annual rings are mostly very hard to make out and naturally that is what we would expect where the trees have overabundant rain and sun. Yet there are pines from tropical areas whose rings look very attractive and well worth a careful test for climatic effects. They grow mostly at higher levels. Two Araucanian pines from southern Brazil, showing 500 years of age, were measured in the Commercial Museum at Philadelphia. Their variations looked very attractive, but there was no success in finding cross-identity.

Cedar of Lebanon and archæological material—This cedar is chiefly found in mummy cases, which from the earlier dynasties show beautiful ring systems, very pronounced but somewhat complacent. The wood is not so good as yellow pine or sequoia, but as approximate dates are known its records are valuable.

The prehistoric ruins of the Southwest have large numbers of pine and fir logs used as beams. These offer the finest records and a very valuable collection has been made. Even the charred ends of beams that remain in some walls of burnt-out kivas give perfectly good ring records which permit the "relative" dating of the construction period. Juniper, cedar, and pinyon have been used in the same ruins and many sections have been saved, but so far little relative dating has been done on them. Engelmann spruce also occasionally is found, but it has failed to be of value. Several cottonwoods give too short sequences to be worth while. Certain buried pines from the vicinity of Flagstaff give very fine ring records with other interesting features.

LOCATION OF TREE

Regions which have been recently cut over will offer the best facilities in getting good specimens from the stumps. A full day or more may well be spent in marking the stumps from which pieces will be cut later by workmen. This selection is very important, for one wants a group that will cross-identify and at the same time will fully represent the forest and the general locality.

Homogeneous area—One needs, in the first place, to collect from a homogeneous area, that is, an area in which the various trees have somewhat similar conditions, enough to give similarity in rings, for on this recognition of the same rings in each depends assurance of climatic effects in the trees and reliability of dating of rings. To limit one's self to a homogeneous area means that the group will not extend to opposite sides of a large mountain. In northern Arizona differences of a few hundred feet in altitude do not usually affect the rings, but differences of 1,000 or 2,000 feet do sometimes affect them. Westerly or southwesterly exposures are somewhat preferable, as that is the direction from which the storms come and there can be no "shadow" or other local effect.

Wide sampling—On the other hand, the group should not be condensed, but should extend a good portion of a mile at the least, so that no alteration can arise from some special condition affecting a part of the group.

Grouping—The tree bored, or the stump cut, is better if not near other trees. Trees under 10 feet apart are apt to have an effect one upon another by undue shading or appropriation of moisture. This causes eccentric growth of the rings, throwing the major radius away from the center of the group. Such eccentricity is rarely harmful to the ring sequence unless very conspicuous, but it may mean erratic or slanting growth and therefore is to be avoided as a rule. While the Arizona pines are naturally isolated, the sequoias are habitually close-grouped; but in spite of this the latter tree rarely shows any effect that can be attributed to nearness of other trees, unless two are almost in contact. But in the coast redwoods close grouping is doubtless an important cause of its failure to cross-identify.

The big tree is surrounded by dense vegetation in the basins and loose vegetation on the ridges; the coast redwood has a jungle about it; the yellow pines, however, wherever they grow, have sparse or actually deficient vegetation about them.

Ridge and basin selection—This is a question of soil moisture and underground drainage, most important factors in the life of the tree, for while other influences may alter groups of rings and completely spoil parts of the record, the moisture-supply in the soil may change the character of the entire record or even make it totally useless. The evident topographic features which control the situation are of course hill and valley, but to make it more specific by naming the extremes, it is called ridge and basin. Ridge and basin sequoias cross-identify perfectly, but there is a great difference in their immediate response to climatic changes, so that the ridge trees show much smaller average growth with vastly greater differences from year to year. This goes so far that the ridge trees nearly always omit many rings in the radius one chooses to study. Only by accurate cross-identification can these omitted rings be determined and correct dating carried past them.

In the yellow pines, ridge and basin contours have the same effect, producing quick-growing, complacent trees in the latter and slow-growing, sensitive trees in the former. With these facts in mind one can usually pick the kind of tree desired.

Bedrock and soils—Lavas and clay soils give usually a small complacent growth to the Arizona pines, while limestone and the porous soil above it give more sensitive growth, which may be increased in size by a richer soil.

Pines and altitude—The Arizona yellow pines at low levels, such as 5,000 feet, are so sensitive to rain that rings are frequently doubled by the two rainy seasons. This characteristic nearly disappears in 1,000 and 2,000 feet of greater elevation, where the most usable records are found. At still greater heights the accuracy of the rainfall record diminishes, as soil and air moisture are more permanent and the tree in its type of ring record becomes more like the California yellow pine and sequoia.

East and west mountain slope—In the southwestern part of the United States, the winter storms coming from the west supply nearly all of the growth-moisture for the trees. The result is that the east and west sides of a large mountain have a distinct difference in climate which shows in the trees (see shadow effect, p. 108). At corresponding levels the west side is wet and the east side is dry. Around the San Francisco Peaks, in northern Arizona, the pines extend to 1,000 or 1,500 feet lower elevation on the west than on the east. Pines on westerly slopes are to be preferred as less likely to be altered by local conditions.

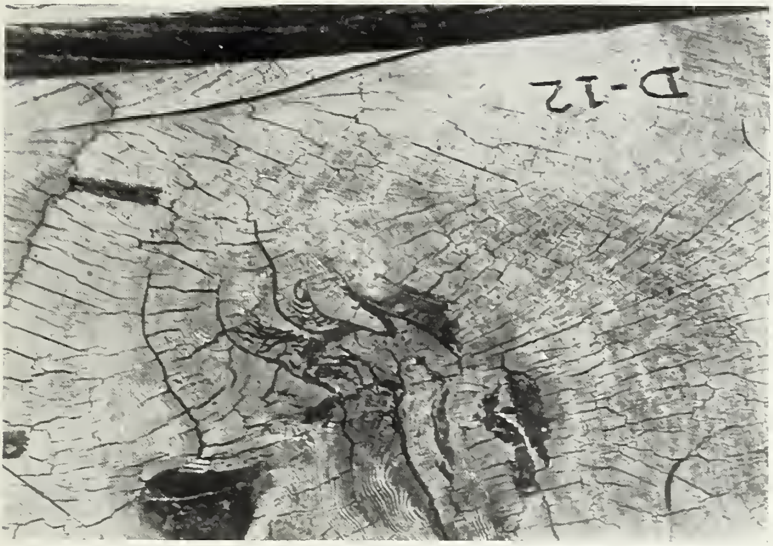
North and south mountain slope—Snow lingers longer on north slopes, and pine trees are able to live under such conditions at lower altitudes. But in the middle elevations of the pine belt no sensible difference has been noted in ring record between minor north and south slopes.

CONDITION OF TREE

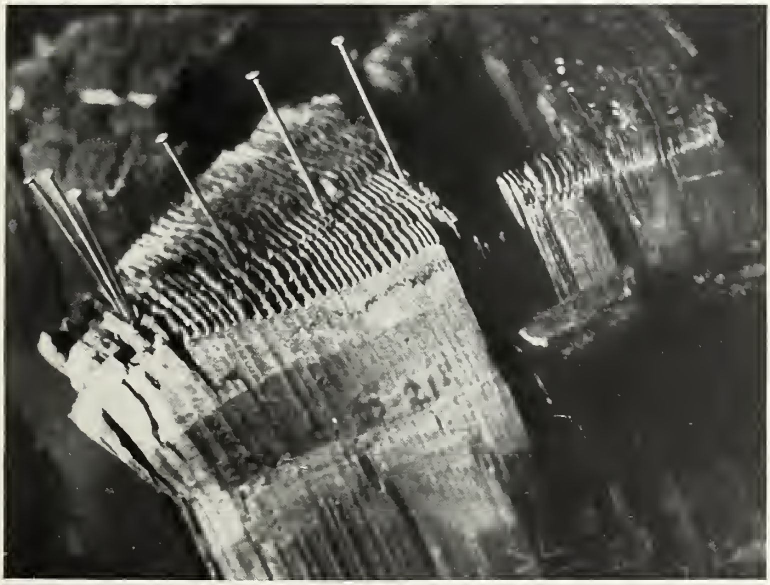
Lightning scars—In standing timber this commonly appears as a white streak from top to bottom of the tree, about 1 inch in width where the bark has been blown away and the wood revealed. The heat of the electric flash has suddenly vaporized the sap and exploded the tree along this narrow line. This usually heals and has no important effect on the climatic record in the tree. The scar is easily recognized on the stump. It is very common in the "buried trees" found in the valley terrace above Flagstaff, which doubtless means that summer thunderstorms were more common in that particular past climate than they are now. Lightning scars are rarely seen in petrified wood, but the writer has a photograph of one in a beautiful specimen from Tertiary levels in Yellowstone Park.

Injured and fire-scarred trees—The major injury to western trees is from fire. This is not always caused by the careless camper or smoker, for the greater number of forest fires come from lightning. A single summer storm at Flagstaff has been seen to start fires in four different trees. In a precipitous country it is the up-hill side of the tree which is more likely to have fire injury, for it is the brush and leaves and needles collected there which hold the fire till it injures the tree. The fire scar is a large burnt area covering from 10° to 150° of the circumference and extending from 3 to 20 feet or more above ground. The tree may recover by covering a small area with new growth or by abandoning all attempts to reclothe the burnt section and using only the root system on the normal side.

Different trees and fire—Fire injuries rarely give trouble in the yellow pine, for they are largely on nearly level ground and there is little vegetation about them. Hence, there is little accumulation of rubbish and a general fire does not linger about an individual tree. The sequoias represent an enormously greater interval of time and so are more likely to show fire scars. Their ages are from 700 to 3,000



A. Fire injury on D–12 (stump) showing repair and gross rings and inclosed bark



B. Center of oldest Sequoia, D–21, showing ring grown in 1305 B.C.; three pins stand at 1300 B.C.

years, compared with 200 to 500 for the pines. The sequoias also grow close together, and in the basins are closely surrounded by other vegetation. So fire once in them lingers and injures the tree. Amongst thousands examined the uninjured trunk has been very rare, perhaps less than 1 in 10, as one looks on top of the stump and sees the history of each tree. The large groves of coast redwood show similar history. Though the custom of burning over the area right after cutting may lead to overestimation of the number of ancient fires, the impression is gained from hundreds of stumps that large fire injury is very nearly as common as in the giant sequoia.

In tree selection the effect of a lightning scar is negligible. The effect of a fire which kills small trees about but does not externally injure the tree under examination is to cause a slight possible diminution in size of rings. In this connection one remembers that fires are more frequent in times of drought and hence exaggerate climatic effects already in the trees. But the effort of a tree to repair a large burnt area changes the ring-size for some distance from the injury and sometimes all about the tree. Hence trees showing large fire injury should not be used.

COLLECTION PURPOSES

In securing records of climate in trees, necessarily length and accuracy of record are the two primary considerations. In the previous pages we have dealt with accuracy alone; now we deal with length, always modified by the necessity of preserving accuracy also.

Cycles and secular changes—The original thought in this study emphasized the tracing of cycles. These are found in relative ring-sizes which can be taken almost at once from the trees without a knowledge of the absolute rain or climatic equivalent. Perfect dating was absolutely necessary and all specimens have received the most careful laboratory handling. It was found by early tests that no especial gain was made by using large numbers of trees (Vol. I, pp. 21–22). But when Huntington studied the big tree for absolute values and secular changes, he did his work on the stump and obtained material which served his purpose without accurate dating. He used many specimens of all ages in order to work out a compensation for age, for that was fundamental.

Best collection methods—To allow for the needs of each of these purposes the best collection includes, first, long records; second, a few younger trees for the sake of certainty in dating the older trees if recent rings are compressed and doubtful and in order to develop a compensation formula for age of tree; and third, borings in the outer parts of living trees in order to get present-day climatic comparisons and to be perfectly sure of the ring of the current year, which sometimes fails to show on the stump.

Long-record trees—(1) Pines. If very large living pines are in moist valley-bottoms, they are not likely to be of maximum age, that is, over five centuries; but if they are near 60 inches in diameter and growing on a ridge or hillside, especially above a dry valley, they are likely to contain a valuable record. Of course, in such cases one checks the estimate by a core from the increment borer. (2) Sequoias. The oldest sequoias are not close to running water nor yet on exposed ridges, where stress of storms does not permit great age, but they are somewhat between these situations and usually near, though not at, the higher levels of the grove. This description applies well to the 3,200-year tree at Converse Hoist and the 3,100- and 3,000-year trees at Enterprise. A 2,800-year tree at Converse Hoist was nearer the top of a low ridge than one would have expected. A number of 2,200-year trees were well outside and yet not far from the thickly covered swampy basins, and they extended up the valleys to the highest levels of the groves. In the lower levels the trees were apt to have a large supply of ground water and some very large trees had only 1,500 to 2,000 years of age, such as the "Big stump" at Wigger's (General Grant Park) and the Dance Hall stump at Calaveras Grove.

Collection for age compensation—Samples for this purpose must obviously be taken from the immediate vicinity of the old trees whose records are to be checked, and in the same topography.

Climatic comparison—In collection for climatic comparison, one uses the general principles of selection already enumerated, remembering that one gets little if anything from young trees. Mature trees are much preferred, and even the largest and oldest, for in such cases the 9 or 10 inches of core cover a great number of years. On the other hand, very slow growing trees from the tops of dry ridges may be impossible to date without some neighboring younger trees, and it is safe nearly always to include a very few younger trees to assist in this operation. Trees very near a road are apt to be erratic from injury.

Age estimates in sequoias—Age estimates are a necessary part of collecting, especially in sequoias. The best criterion is the size of the outer rings, coupled with the total diameter of the tree. A promising tree should be over 20 feet in diameter above the bulging base, or near 25 feet at the very maximum. The rings at various places in the outer parts should get down to a few tenths of a millimeter or about a hundredth of an inch. On most of the very old trees there is a burnt space in which a few chips or bits of charcoal will give a sample of the rings. An increment borer is still better and may be used through a thin place on the bark of a living unburnt tree. The largest tree, showing over 30 feet in maximum or bulge diameter, if near running water, is not likely to add much to our climatic record. But if such a tree is on a dry hillside its age is worth investigating, and if it still promises well, some apparatus for boring it to the center could be devised.

III. RADIALS

SELECTION

An essential part of this study of climate and trees has been the laboratory work on the rings, by which the actual wood from the tree is placed under microscope and measuring-machine. In this way specimens from different trees may be compared together and an accuracy reached which would be hopeless in work on the stump. By laboratory means, cross-identification and correct dating are obtained before measuring and the measuring can be done to any desired accuracy which the rings permit. Hence it is essential to secure ring specimens which represent the tree, to get them to the laboratory without injury, and then preserve them in such a way that they can be used over again or referred to subsequently for any desired purpose.

Definitions—It is obvious that such ring specimens must be cut across the rings in order to display the proper sequence. The ideal form, therefore, is a radius of the tree, carrying an unbroken series of rings over all parts of the tree's history which are worth while. Such pieces are here referred to as tree-samples, ring records, radial pieces, or simply radials. Of course, they may take different forms, depending on various conditions of collection; for example, whether they come from living trees, fallen trees, or stumps.

LIVING TREES

The main point in sampling living trees is to get a short radial sequence of rings without injury to the tree. The best instrument for this is the Swedish increment borer, which will be more fully described in a subsequent chapter on instruments. These borers will not go into hard woods nor even into junipers, but they work well in pines.

Direction of boring—If the tree is on a steep hillside, it is usually more convenient and customary to bore on the up-hill side. Theoretically there could be a difference in the rings between the up-hill and down-hill side of a tree, but no such difference has been noticed. Other things equal, it is well to eliminate the possibility by being consistent throughout a group. If the ground is generally free from steep inclination, one should adopt a certain compass direction and use that consistently in the group. Early investigation showed about Flagstaff a slight average increase of growth on the north or northeast side of a tree, due to lingering of snow in the shade of the tree, but this is probably of little or no importance in radial selection.

Height above ground—Height from the ground, if well below the branches, has not been found to introduce error. So far as observed, the differences at different heights are less than the differences between different trees. Of course, in most cases the differences are practically none at all. This subject of taper study or vertical uniformity will be treated on a later page. A boring within a foot of the ground makes one feel that complex and difficult corrections are needed because of the root influence, and the ring record therefore is inferior. On the other hand, if the boring-hole is made over 2 feet from the ground, it may injure slightly the value of the tree for lumber. The average height of pine stumps about Flagstaff is 16 to 20 inches, sometimes going to 2 feet. The lumberman knows that interior defects increase toward the root, and there is always a little waste at the lower end of the butt log. In choosing the exact spot to bore it is better to try a slightly projecting part of the trunk, for there is less danger of encountering absent rings which might render dating difficult. One must be careful in boring fallen trees to note whether they still have roots in the ground and are dry or moist. If they are still rooted or not thoroughly dried, the sapwood may be distorted with irregular growth or irregular swelling from moisture.

Root rings—Ring sequences have been identified from roots of trees and in some cases such records seem usable. These, however, have never been included in the averages, from the feeling that root rings, even in large branches of the root, must be subject to other conditions than the trunk and may not be consistent. Sometimes, in well-watered pines, early rings in the lower trunk near the root may be very large.*

Crown rings—Rings near the top of the tree and in larger branches show close similarity to rings in the lower trunk. Though their actual size is smaller and sometimes microscopic, the sequence of sizes, of the tree record, is nearly the same (see fig. 1, p. 24).

Boring the sequoia—Using the increment borer on the sequoia has rarely seemed worth while, except for some special purpose, such as tests on young trees for infancy rings, estimates of age, and so forth. The reason is the enormous thickness of bark of the sequoia, especially in the lower 15 feet, and the distortion of rings due to bulges in the same region. With a ladder one could get useful specimens.

The 1-inch tubular borer—The tubular borer so far has not been satisfactory on living trees, not because it hurts the tree but because it is slow and difficult in operation. An 18-inch core from a 350-year tree in the lava-bed near Flagstaff took nearly two hours of very hard work. When it is needed, no doubt a suitable borer will be easy to construct.

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*This was observed in a tree which once stood in the flat south of the county hospital at Flagstaff, about 2 miles north of town. The tree was cut down in the 1880's and was renowned for its size. Recently Mr. L. F. Brady copied on paper the rings in the stump, which was badly burned. When I saw it, the stump had been blasted out and thrown away, but fragments showed extremely large and complacent rings near the root. The dating was uncertain, but it was probably nearly 500 years old at time of cutting.

FALLEN TREES

The chief work on fallen trees was done in the Calaveras Grove of sequoias. The bark of these trees lasts 10 years or so after the tree has fallen. The sapwood weathers off in something over half a century. Heartwood has lasted a hundred years in the open air, but in the case examined the wood was badly decayed and little of it was left, as shown in Plate 2. It has been a disappointment not to find logs lasting far longer, for example, a thousand years; for if very large ones could be found they might have very old ring records. Apparently even the wonderful qualities of the sequoia sap will not preserve the wood indefinitely. Fallen trees give the chance of boring at any height and from that arose the vertical uniformity or "taper" tests given below.

In the Calaveras Grove there were three classes of fallen trees, so far as dated records were concerned: (1) old tree-trunks without sapwood, so that the date was unknown; (2) trees showing sapwood, with approximate date of falling; and (3) those whose date of recent falling was known. So to insure correct dating, all three were included. Thus an overlapping group was obtained, which by cross-identification produced correct dating for the Calaveras trees. But all this care proved unnecessary, for the first radial examined, as well as all the rest, readily dated in terms of the trees in the southern groves.

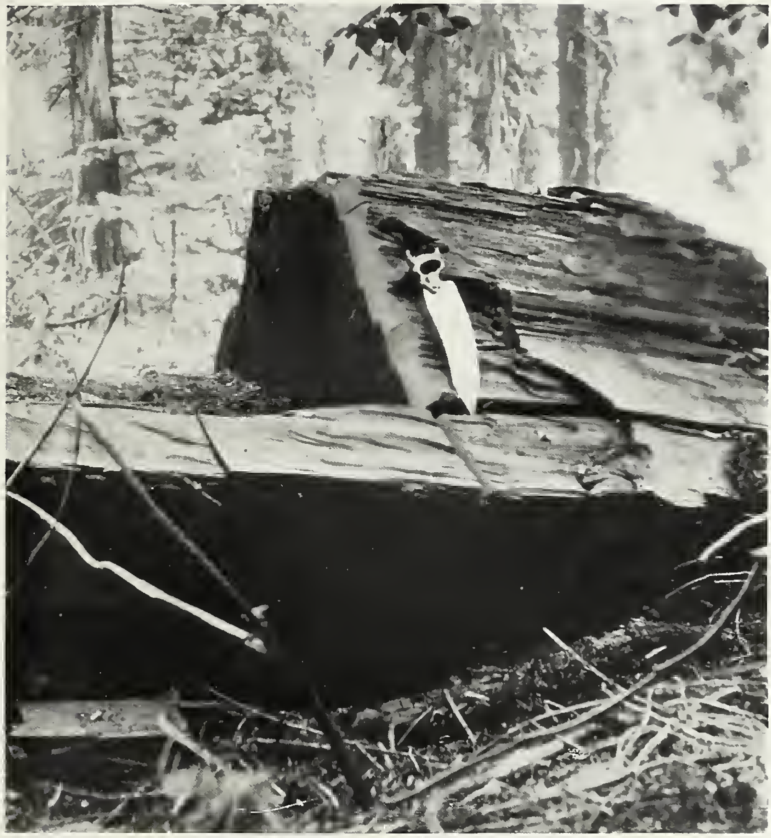
STUMPS

Collection from stumps permits many forms of which the full section is only possible in the case of small trees. Thus full sections have come from the white pines of the American Arctic and from the beams of the ancient ruins. At the start, full sections were made of the early Arizona yellow pines, but they have proved so unwieldy and difficult to provide space for that even from these radial samples have been cut, which give the ring sequence from center to outside. So methods of collection necessarily adapt themselves to the size of the trees. In the vast majority of cases a piece is cut from the stump, and that process is described below.

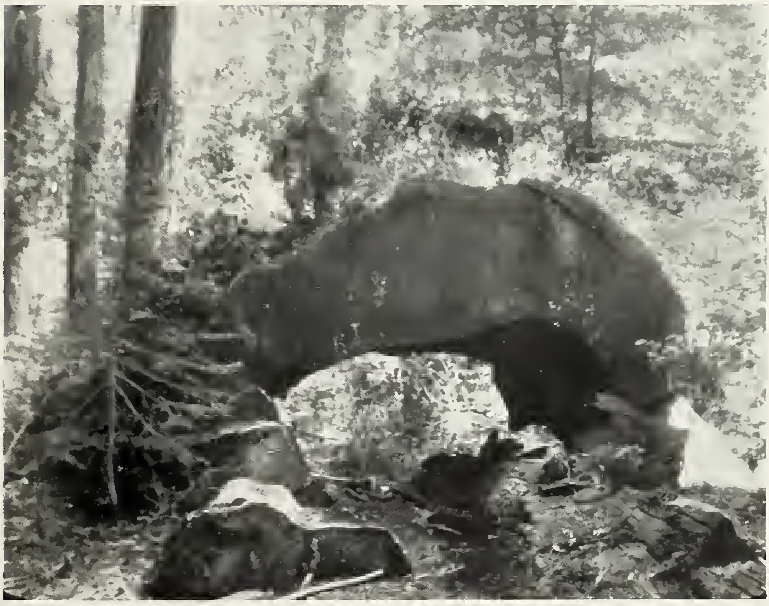
Shape of stump—In felling a tree a notch is first cut on the side toward which the tree leans and will fall. This undercut goes perhaps one-fourth way through. In big trees it becomes large enough for men to stand up in. Then a two-man saw is started in horizontally from the opposite side at a slightly higher level. As the saw enters the tree, the weight of the tree will pull away from it and not make it bind. Sometimes the tree is leaning so heavily that as the saw gets deep into the trunk, the strain on the remaining wood is tremendous and it cracks badly in lines parallel to the saw. If its own weight does not keep it from binding the saw, steel wedges are driven in the cut to force the tree up on that side. The tree usually begins to fall some time before it is completely cut from the stump, the portion that is uncut breaking off at the level of the undercut. The stump then shows the sawed surface for two-thirds of the diameter on one side, the chopped surface of the undercut a foot or two lower on the other side (in the big trees), and between these a broken and splintered space where the wood broke in falling. Sometimes the tree does not fall of itself when the saw is approaching the undercut, and then instead of sawing it completely in two, which would be dangerous, sticks of dynamite are placed in the remaining attached portion and the tree blown loose. This is apt to blow the stump to pieces, as happened with D–18 of the early sequoia group. That sample was therefore cut from the end of a log which had been 50 feet or so above the ground. So nearly all stumps have a flat top, which will exhibit from a little over one-half the diameter to more than three-quarters. This restricts the choice of radius a little, but reduces the amount of sawing in making the cuts for the radial piece.

Selection of radius—In visiting a cut-over area with multitudes of stumps, the first consideration is the apparent excellence of the rings and the ease of cutting a radius which contains good readable ones. In the Arizona pines this gives very little trouble. In these trees the radius chosen and marked merely fulfills consistency regarding points of the compass and contour of ground, and avoids fire-scars, lobes, and knots in the stump-top itself. The piece cut out very often takes the whole diameter. In the sequoias perhaps only 10 per cent are without defects, and the inspection of stump-tops becomes an important matter requiring from half a day to a couple of days. Deep fire wounds in healing often inclose large masses of bark, and frequently such scars have a considerable area of sapwood which has never turned to heartwood. Such defects are always interesting for the history they tell and are easily avoided in picking a radius. This appears in the photograph of sequoia D–12 in Plate 1.

One of the greatest difficulties with small fire-scars is the extensive break they sometimes cause in the continuity of the rings. The fire so alters the growing layer that for some distance away from the burnt area the wood will crack and it may be very hard to say whether the crack is within one annual ring or between two. Lumbermen say that this cracking or checking takes place in the living tree. It is attributed sometimes to temperature changes—frosts in the weakened wood—and sometimes to wind. At any rate, in a weathered stump such a crack becomes worse and makes it difficult to use otherwise good material. In such cases it is always best to cut a separate small



A. Weathering in 60 years, CV–4; bark gone, sapwood mostly gone; Calaveras Grove



B. Weathering in 125 years; CV–3, sapwood and center entirely gone; Calaveras Grove

radial piece extending a hundred years or more on each side of the questionable years, from some other perfect part of the stump. This new piece bridges over the doubtful point. It is just such procedure as this which makes the dating entirely reliable. Knots or buried branches give practically no trouble, except at the very center. The lower parts of a sequoia whose bark has turned to the notable tan color of youth seem to have no branches. They probably all disappear as the rings lose that immense size called the "infancy" stage. So in selecting a radius for cutting it is highly important to escape gross-rings, lobes, and fire-scars. Items to be recorded are the length of radius, bulges or slope, direction and amount of slope of the ground, and neighbors. If the tree has grown eccentrically one would slightly prefer an average radius if the rings are not too much inclined. Bulges as a rule are below the level of cutting, but they may affect the slope or vertical inclination of the rings from the enlargement they produce in the base of the tree. In recent collections the slope of the outside has been measured with a simple inclinometer.

The v-cut—Even in small trees the v-cut illustrated in Plate 3 is now the standard form found practicable. Such small pieces are v-shaped or triangular in cross-section and made by two slanting cuts with a saw, meeting at a depth of 1 to 6 inches below the surface. With a long saw on large stumps the slanting cut is made by driving two spikes at a slant into the stump top, placing a board against the spikes, and resting the saw against the board.

The size and weight of the radial piece cut out depends on the spacing of these cuts. Two inches is taken as the standard practical width and depth in big trees. If the v-cut is made from a weathered stump, as is usually the case, the cracks in it allow it to drop to pieces as the saw releases it. To aid in fitting these together the distance from the bark in inches is marked on each piece as it comes loose. These pieces are collected by an assistant who accompanies the sawyers and are all put in one bag, which is marked with the radial or tree number. These small bags are finally collected in a large canvas bag for transportation.*

PREPARING THE RADIAL

Arrived at the laboratory, the pieces are taken from the sacks and carefully fitted and glued together and wired or screwed to a right-angle mount of standard size which permits stacking. This mounting consists of a base and back, each 4 inches wide by 8 feet long, 1-inch wood, with heavy square end-pieces. These mounts, being all of the same size, will stack one on top of another against a wall or with very slight bracing, so that at a glance one may look over the entire collection.

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*When this work is done by a lumberman who can not bother with bags, the spacing of the cuts should be wide enough to make the specimen hold together.

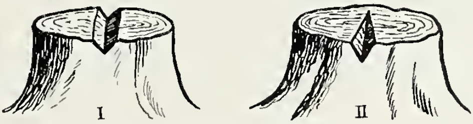
The original surface of the stump is placed downward in the mounting, thus showing the freshly cut surfaces, which at a little distance below the stump-top are in better condition. One or both of these surfaces is smoothed with a rasp or file; then after careful inspection of the rings a line or band is marked where the measuring and dating will be done. For this purpose two parallel lines a half inch or more apart are put on, as nearly straight as possible. The space between these lines is then shaved with a sharp razor. This leaves a superb surface for measuring the rings. The lighting direction is important, but by a little practice the best position is readily found. The only special caution at this stage is that each break in the wood which has been glued should be marked and shaved along the crack so that dating and measuring can be carried past it without the slightest chance of error, but this rarely presents any difficulty.

RADIAL STUDIES

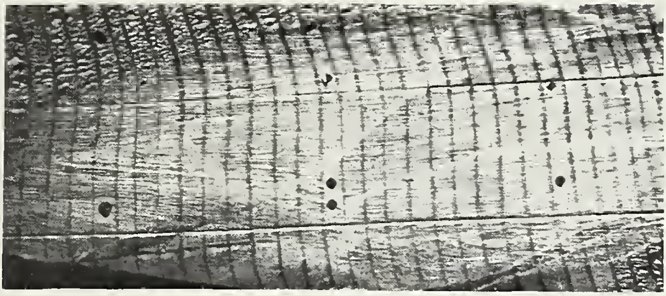
CIRCUIT UNIFORMITY

By circuit uniformity is meant the close similarity of the ring records in all directions from the center of the tree. The fundamental importance of this was fully recognized in the first formative period of this investigation. Cross-identification between different trees was first used as an essential in 1911, but this identity between different radii in the same tree was noticed in the very first trees measured in 1904. To describe where it has been found would be to enumerate almost every tree worked upon. Even groups that do not cross-identify well show circuit uniformity. This does not mean that the different radii are equal, but that the relative ring values are closely the same in all directions. So the present topic is for the purpose of calling attention to a few exceptions. Circuit uniformity is modified in three ways—by eccentricity, lobes, and gross-rings.

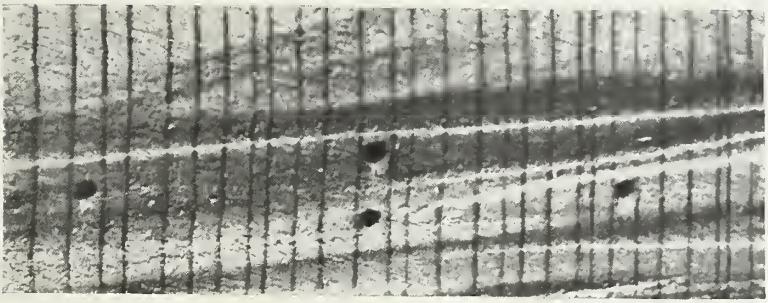
Eccentricity—Slight eccentricity is very common. It becomes noticeable in perhaps one-third of the stumps examined and occurs in perhaps one-quarter to one-twentieth of the trees sampled. It merely means more growth on some one side than on the opposite. It is a common effect of group pressure and frequently occurs when two trees grow very close together. The maximum growth is then away from each other. It may be due to other causes. In the first 25 Flagstaff yellow pines there was 12 per cent more growth to the northeast than in the opposite quadrant, attributed to better moisture conservation in the shade of the tree. Eccentricity, unless excessive, need have no effect whatever on the tree record, and even if excessive it can usually be evaded. The most extraordinary case ever noted was a



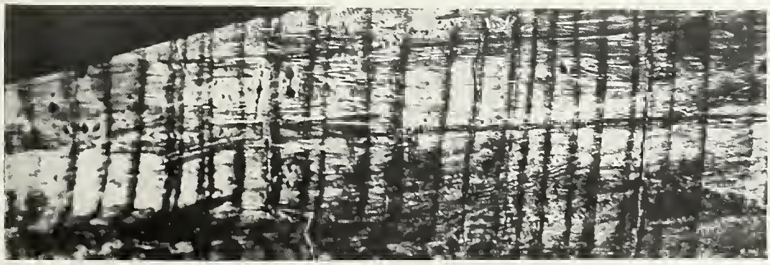
A. Forms of v-cut on stumps



B. Complacent sequoia rings, D-8, grown in wet basin



C. Sensitive sequoia rings, D-4, grown in uplands



D. Hyper-sensitive or erratic yellow pine rings, Pr. 62, grown near lowest yellow pine levels, Arizona

Scotch pine from Ös, Norway, which had a 3-inch radius on one side and a 9-inch radius on the other. The maximum radius was used and it cross-identified in a perfectly satisfactory manner. Several of the trees from that locality showed a very rare characteristic in having the eccentricity change its direction as the tree grew older, due probably to change in surrounding growth. This was less easily avoided. Forest Service men usually prefer a mean radius in eccentricities, but in this work it is not desirable, because in that kind of a radial the rings are apt to be inclined, making perpendicular measurement more difficult.

Missing rings—In eccentricity the crowding in the shorter radius causes some rings to disappear altogether instead of merely becoming more minute. The same failure of rings is very apt to occur between lobes, especially in junipers. Hence in boring trees it is safer to choose the lobe itself than the depression between lobes.

Lobes—In the case of lobes, or the scalloped outline of a tree-trunk, the variations observed in eccentricity are greatly exaggerated, in fact, so much so that trees like juniper and pinyon that go strongly to lobes can not well be used in ring studies. In an extreme, a given ring can not be traced from lobe to lobe. Such a tree of course has doubtful value.

Pines and sequoias, however, have only a negligible lobe effect, except during the "infancy" period of the sequoias, when the lobes are very marked. They disappear in the early "youth" rings, which are really the earliest ones of any chronological value. When not pronounced, either the lobe itself or the depression between two lobes may be taken as the location of a radial, for the rings remain at right angles to its direction.

Root influence—Lobes are usually more pronounced at the base of the trunk and show evident connection with the roots. Since the root supplies the sap which passes up the trunk and, in passing, forms the ring, the rings, it would seem, depend upon the way the sap spreads out around the tree as well as upon vertical movement. So in old trees whose rings are naturally crowded, we find some missing here and there in the circuit without much lobe effect being evident. In the general use of at least five trees in a group, such lapses practically always come to light.

Gross-rings—A difficulty in the selection of radius in sequoias has been occasional radii where the rings are greatly enlarged. These are called "gross-rings." They are probably associated with the success of some certain root and therefore formed lobes or projecting curves about the trunk when the tree was growing at that size. Sometimes these areas extend directly to a projecting curve of the stump outline and their relationship is evident. They not merely exaggerate immensely the average growth in certain parts of a radial line, but they do not hold to one radial direction and any straight line; cutting them at an angle has inclined rings, which therefore have an added fictitious size.

Gross-rings only moderately represent climatic change. In an old study it was found that gross-rings in one tree corresponded to similar rings at that date in about half the other trees. They probably occur when for some reason the tree is having rather successful growth, and so they roughly indicate favorable conditions. It would probably improve the curve of the tree's growth if they were reduced to a size somewhat less than half-way between normal and their actual size. The inclination which they so often exhibit can be corrected by measuring in a different angle or by a multiplying factor. But either one adds greatly to the labor of handling large quantities of data in tables.

Spiral gross-rings—A prehistoric section, H–9, from the Aztec ruins has a spiral of enlarged rings, which took about 12 years to make the circuit. It is impossible to tell from the specimen which way the enlargement rotated. The 9-foot Sitka spruce in the American Museum of Natural History shows at some 8 or 10 places about the circuit spiral enlargements with a very slow rotation.

VERTICAL UNIFORMITY

Outside tests—The close resemblance between ring records at different heights in the same tree was assured for the yellow pine a score of years ago, but has only recently been tested formally for the sequoia. During the trip of 1925, a windfall in the Springville region offered such a good opportunity for tests of this sort that it seemed worth while to take advantage of it. This tree, whose uniform trunk was about 15 feet in diameter, had been blown down in 1901, according to Mr. Elster, close to the houses at Enterprise, which had been started as a mill-site some three years before. The tree is lying there in excellent condition. The Swedish increment borer was used at 9, 15, and 35 feet from the base of the roots and thereafter at each 20 feet, to a distance of 235 feet from the base. At 255 feet small pieces were cut with a saw, in wood which had been a living branch and in a dead part which had been the main stem. This last showed nearly a thousand years in the radial and has not yet been identified, probably on account of the smallness of the rings. Yet 900 years in the living branch were readily dated, and at 20 feet below this point the cross-identification is perfect, though the branches begin nearly a hundred feet lower down. The lowest boring was well within the root system, close to ground-level, and does not identify well after 1700. With this exception, similarity in heartwood record, which extends to about 1800, is striking at all heights above the ground. But the sapwood rings show profound differences, due it is thought (p. 101) to irregular swelling from the moisture which has filled them for years. Figure 1 shows parts of the heartwood curves, from 1550 to 1590, including the year 1580, which is very distinctive when taken together with 1548 and others. Figure 2 shows the variable sizes of sapwood rings, interfering greatly with dating and presenting a most unusual condition in the sequoia.

The curious fact became evident that the tree grew in places a long time after falling, for most of the borings show a serious injury about 1901 and some show no growth after that. But some show continued growth up to 1915. This appears in figure 2. Evidently roots still in the ground supplied moisture and supported growth for more than a dozen years after the tree had fallen.

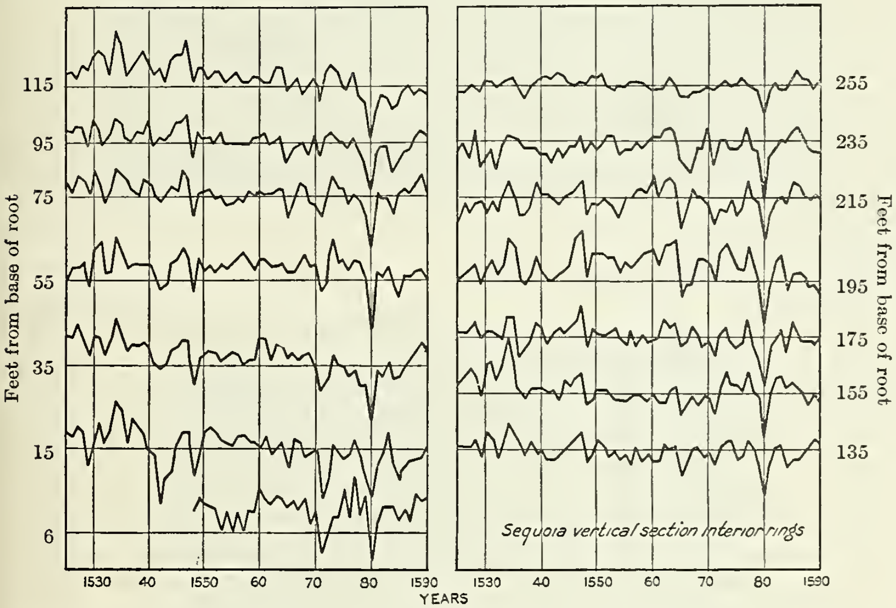


Fig. 1—Heartwood rings at different heights in the sequoia; total height 265 feet; vertical uniformity nearly perfect. Scale × 7.5; horizontal line with each curve represents 1 mm. growth

Naturally, this matter of longitudinal or vertical uniformity was considered and tried out informally in the early work on this subject, and, so far as the eye could tell, the same rings existed at different heights. The fact that cross-identification applied equally at different heights in the trunk of the tree was held sufficient at the time. For example, D–18 and D–20 were each cut about 50 feet above ground-level, and yet they cross-identify and otherwise appear exactly as sections near the ground. The recent work of MacDougal and Shreve on the longitudinally bisected tree is adding to our knowledge, and it is desirable to see such studies applied to mature big trees and to yellow pines, each in its natural home.

Central tests—A recent test at the center of a sequoia came about in this way. Stump numbered D–22, whose picture is shown in Volume I, Plate 7, *A*, was sampled in 1918. It had over 3,000 rings, but other innermost ones were missing on account of a large hole in the center. The earliest ring found was 1087 B. C. The estimated radial loss in wood at the center was 12 cm. (some 5 inches) or about 75 rings (Volume I, p. 52, table 5). The "butt" log from this stump was lying not far away. In 1925, it appeared that in the upper end of this log there was no hole and the rings originally filling the hole in the stump might be found and measured at this point. So a special cut was made crossing the center and extending a few hundred years along the best radius. This direction proved to be away from the original radius, but in the sequoias that practically never makes any difference. This cut was 12 feet above the original cut. It was hoped that the new piece would carry a record even beyond D–21, the oldest of all the sequoias. But this wish was not fulfilled, although this center V-cut proved very interesting. It cross-identified with perfect ease and entire certainty. The central growth was in 1115 B. C. So only 30 years were gained, but it thus carried a record back very nearly as far as D–23 nearby, whose innermost complete ring was 1122 B. C.

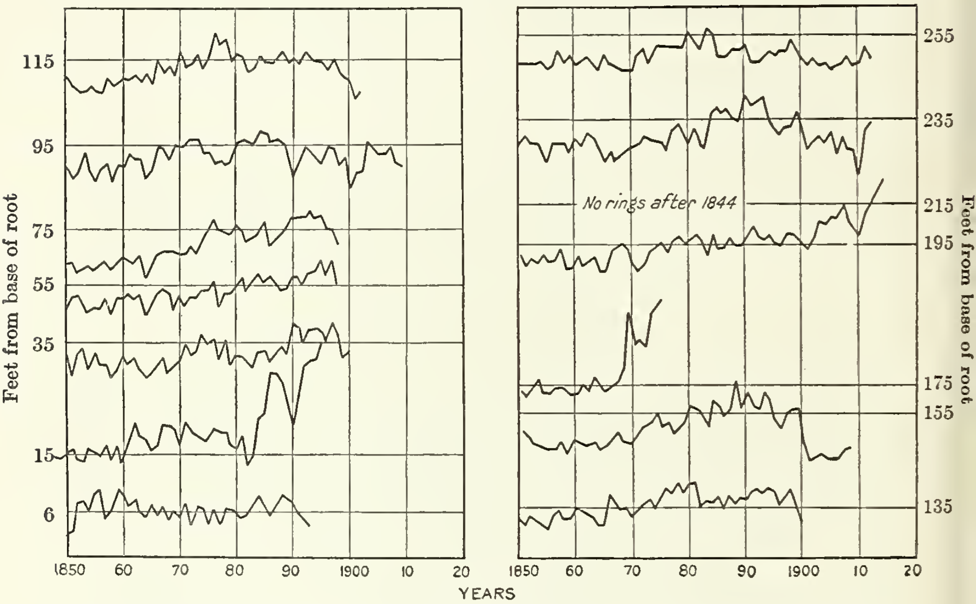


FIG. 2—Sapwood rings in fallen sequoia; irregular growth after falling (in 1901) is shown with distortion due to water-soaked condition. Scale × 7.5; horizontal line with each curve represents 1 mm. growth

A. Fallen sequoia, Enterprise, on which vertical uniformity tests were made

B. Sequoia "California," Enterprise; and Mr. C. A. Elster

At the same visit in 1925, it was remembered that D–23, whose earliest ring has just been given, also had a large hole in the center, with an estimated loss of 14 cm. or 80 years. This D–23 or Centennial stump, has a large fragment lying near it on the ground, but a search showed that only some outside pieces were there and the central parts were entirely missing. Thus, there is no chance of extending the record of D–23. In this connection it may be added that the oldest tree, D–21, whose earliest complete ring is 1305 B. C., has only an inch missing at the center, perhaps a half-dozen years, and so there is no chance of material extension of that record. The central part of that stump is carefully preserved and mounted in the laboratory.* It is shown in Plate 1.

A tree known at Springville as "California" and numbered D–47 in my series was cut years ago for the purpose of building a sequoia hut. It stood isolated, about half a mile from the Centennial stump in a southerly direction. The stump has a very high, projecting center, with steep ax-cut slope to north and a walk-way all around where slabs of wood were removed. The top and nearly all the trunk lie off to the east, with a smooth sawed face 15 feet in diameter, as shown in Plate 4. My v-cut was made on this face, extending past the center. Almost at the last moment of my visit one of Huntington's grooves (but no number) was found on this stump, showing that he had counted the rings. So for comparison we made a short central v-cut. This was about 12 feet above the ground and also about 12 feet below the full radial taken from the log. This will be studied in connection with ancient records.

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*The smallness of this hole where the infancy rings used to be, suggests that this cutting-level was 20 or 30 feet high on the tree when it was a sapling. If so, the ground about this tree has filled rather than eroded. The adjacent contours make this possible.

IV. RINGS

During and following the processes of cross-identification and dating, described in the previous volume, the best ring records are picked out by a form of selection, first between the different trees of the group, and second between different parts of each tree record.

SELECTION IN GROUP

During cross-identification it is very easy to see which specimens conform best to the group type and which ones conform so little as to be discordant, for in all the groups used a group type is evident. It becomes, then, easy to recognize any specimen which for some reason or other, perhaps a fire injury or a different water-supply, does not agree with its group. Such specimens are obviously so far from the average that probable errors are diminished by their omission and their values are not included in the group average. Such individuals are usually very few in number, in the majority of groups none at all, and they include of course the ones which can not be cross-identified.

MEAN CONFORMITY

In judging whether any tree should be retained in the group a criterion called "mean conformity" has been very extensively used. It is the agreement which any individual shows to its group or type. In effect, it is an added weight given to individual specimens which have the best support from other members of the group.

Quantitative conformity—An actual numerical value of this conformity could be derived by mathematics (by mean residuals from group averages), but it would be a long process and the results at the present stage would not be worth the labor; for after familiarity is reached a conformity coefficient can be estimated, as in a multitude of different scientific observations. However, in connection with the selection of best sequoia records for comparison with Arizona pines, a quantitative value was reached in a practical way. The Arizona variations were kept fresh in mind as each sequoia record was reviewed. The number of Arizona features found in each sequoia for each of the last five centuries was carefully recorded and the total placed against each sequoia as its weight or conformity. Those having the best conformity were then selected for certain comparison problems. This is a good practical method. Other selections have not been made on so large a scale and did not need such formal organization, but nearly all have been based on some modification of this process.

Weighted means—After mean conformity of each member of a group has been obtained, it may be used simply to exclude poor records, so that the average of the remainder will be improved. If some approach is made to a numerical value of this conformity, then it may be used to obtain a weighted mean. This was done in the case of the four best sequoias selected for dating comparisons with Arizona. This was a long process, but its application did not make enough difference for one to feel that its universal use is necessary.

MEAN SENSITIVITY

Another criterion which helps in selecting the best record has come into practical and important use, even though the computation of numerical values is a refinement not usually applied. It is called mean sensitivity (see also p. 104) and is an inherent character in each individual. It may be defined as the difference between each two successive rings divided by their mean. The quotients are arranged in groups of 10 or some other number of years, and listed as the mean sensitivity of that period. Plate 3 shows the appearance of rings of different sensitivity. The first section (*B*) came from a sequoia which grew in a swampy basin about 15 miles east of the General Grant National Park. The tree had a "complacent" growth, with all rings of nearly the same size. Its mean sensitivity is 0.11. The second is a sensitive sequoia which grew near the top of the mountain, 800 feet higher up, with a limited water-supply and therefore more dependent on the moisture of each year as it came. Its rings have more character and individuality, and the changes from ring to ring are much more evident. The mean sensitivity is 0.33. The third is a hypersensitive dry-climate yellow pine near Prescott, one of the 10 used in the curves of Prescott tree-growth already described. It grew near the lowest limit of the yellow pine. Some of its rings, such as 1841 and 1857, are so small as to be found with difficulty. Its variations from year to year are extremely large, and its mean sensitivity is 0.64.

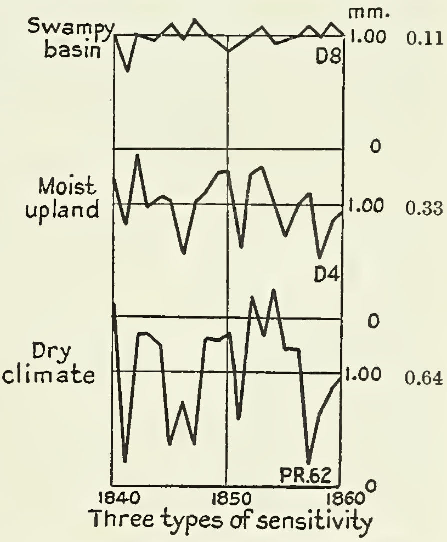


FIG. 3—Mean sensitivity and soil moisture

The way these variations in sensitiveness look in plotted curves is shown in figure 3, in which the curves of growth of these three trees show percentage departures, each from its own mean. The different character resulting from the different environment is at once apparent to the eye.

Practical application—The practical method of handling mean sensitivity is to take the sum of all the changes in 10 years without regard to sign and divide by the sum of the 10 years' growth. This is the way it has been used in the limited mathematical tests. As a matter of fact, high sensitivity in a ring sequence is often apparent to the eye, as anyone can see in the illustrations, and in much exploring work the eye estimates have been the practical and rapid way for using this criterion in judging between ring records.

SELECTION WITHIN RECORD

The recognition of the preferable parts of a sequence of rings comes from an understanding of the natural divisions of a tree's ring system due to age and the recognition of the various kinds of errors and difficulties in the rings themselves. Most important of all perhaps is a knowledge of the meaning of rings in terms of their environment. This last part of the subject is discussed in Chapter VIII.

PARTS OF A TREE'S RECORD

All parts of a tree's record are not equally useful. For purposes of description a good record may roughly be divided into infancy, youth, maturity, and age. These are largely recognized by the size and character of the rings.

Infancy rings—These are most easily found in the sequoia and consist of a central series of extraordinarily large rings, sometimes 2 cm. in width, 10 to 50 in number, showing practically no variation except a successively diminishing size. They are very soft and in very old trees often disappear, leaving a conical hole extending to some height from the ground up into the tree. This is probably the explanation of the rather common central hole, sometimes untouched by fire, as shown by study of stumps. This was formerly attributed to other causes, but some recent identification of the central parts of very old trees described above under "Vertical uniformity" have favored this view.

Youth—The youth of a tree is evidenced by large complacent rings, usually largest in the center and outwardly growing regularly smaller. Speaking from an economic point of view, the tree at this time has to build a large trunk in order to support the growing top and resist wind. It is true, as Antevs pointed out, that at this stage the tree shows large, less sensitive rings. In the yellow pine this period is likely to be 20 to 40 years, but even in these immature rings in many trees cross-identification is perfect almost to the center. This is not always so, and often it is best to drop the inner 20 rings.

The youth rings of the sequoia cover perhaps 300 to 800 years. It is the region where the rings are large and show a gradual diminution. Cross-identity carries through it usually with perfect ease. It is not always easy to recognize the end of this period. In rare cases a tree gets down to small growth in 200 years. It is possible that tests of mean sensitivity would provide a means of judging. In addition, actual climatic change enters here as a variable. A considerable number of the dated trees started near 300 B. C. and show the reduction in ring-size near 400 to 600 A. D. It is probable that there was a climatic drying at about that time which helped these trees to reduce ring-growth.

Maturity and age—Maturity in pines and sequoias covers the time from the attainment of full height to the decay at the top which indicates old age. During this period the rings have their best sensitiveness, though almost equal sensitiveness may last into old age, when the rings become smaller and possibly a trifle less sensitive and yet a trace more erratic. That is, there are longer periods with little variation, broken by a little more frequent complete disappearance of a ring from the sample under study. The growth has gone to some other part of the circumference. These are the unusual cases. It has never seemed desirable to discard the outer parts of a tree so long as the rings were certainly identified.

RING ERRORS

Superfluous rings—The one fundamental quality which makes tree rings of value in the study of climate is their yearly identity. This is sometimes disturbed by the presence of too many or too few rings. Superfluous rings are due to doubling. This is a climatic phenomenon to which some trees are especially liable, probably from their location and rapid growth. But let us keep clearly in mind that superfluous ring formation is the exception. Out of 75 trees collected near Prescott, only 4 or 5 were discarded for this reason. Out of hundreds near Flagstaff, none have been discarded on this account.

Nearly 200 yellow pines and spruces from northwestern New Mexico have produced no single case of this difficulty. The sequoias from California, the Douglas firs from Oregon, the hemlocks from Vermont, and the Scotch pines from north Europe give no sign of it. On the other hand, 10 out of 16 yellow pines from the lower levels of the Santa Rita Mountains south of Tucson have had to be discarded, and the junipers of northern Arizona have so many suspicious rings that it is almost impossible to work with them. Cypress trees also give much trouble. Trees whose extra rings can not be exactly identified are always excluded in part or as a whole.

Missing rings—The other difficulty connected with yearly identity is the omission of rings. Missing rings occur in many trees without lessening the value of the tree, unless there are extensive intervals over which the absence produces uncertainty. A missing ring here and there can be located with perfect exactness and causes no uncertainty of dating. In fact, so many missing rings have been found after careful search that they often increase the feeling of certainty in the dating of rings.

Missing rings occur when autumn rings merge together in the absence of any spring growth. This rarely, if ever, occurs about the entire circumference of the tree. There are a few cases in which, if the expression may be excused, I have traced a missing ring entirely around a tree without finding it. I have observed many cases in which the missing ring has been evident in less than 10 per cent of the circumference. Some are absent in only a small part of their circuit. I have observed change in this respect at different heights in the tree, but have not followed that line of study further. It can be studied in the longitudinally bisected tree. A missing ring is often represented by a slight enlargement of the red autumn ring of the previous year.

One sees from this discussion what the probable errors may be in mere counting of rings. In the first work on the yellow pines, the dating was done by simple counting. Accurate dating in the same trees (19 of them) later showed that the average error in counting through the last 200 years was 4 per cent, due practically always to missing rings. A comparison in 7 sequoias between very careful counting on the stump and accurate dating in 2,000 years shows an average counting error of 35 years, which is only 1.7 per cent (Volume I, pp. 15 and 45).

Simulated doubles—In the process of counting and dating rings in Arizona pines, two sharp red rings sometimes occur close together, giving the appearance of a double and leaving one in doubt as to whether one year or two is involved. In such cases the following probabilities apply: If the tree has other obvious doubles, the case in hand is likely but not certain to be another doubling. If the two red rings are unequal in size and the smaller one is inside, that is, nearer the center, it is likely to be a real double formed by the spring drought. If the smaller one is outside the larger, it is probably a separate year. If the two rings are equal and either one shows a further doubling, the two rings in question are separate years. If the case is still doubtful, cross-identification may settle it. But if that fails, the doubtful part should be discarded. The most tantalizing case of this kind that I have is an early historic beam from Pecos, KL–I, in which all kinds of doubles are exhibited.

Reinforced rings—Certain groups of prehistoric specimens from the Wupatki National Monument, northeast of Flagstaff, show heavy reinforcement in the youth rings of many trees. That consists of very hard tissue formed during the rapid spring growth, so that each ring is greatly expanded in one direction and somewhat diminished on the opposite side. This gives the appearance of a series of crescents on one side of the tree section. It usually interferes completely with the rain record in the tree, but at the same time has a strong climatic significance as an indicator of heavy spring winds.

Other false rings—Other abnormal rings are sometimes produced. Sequoia radials occasionally show certain "pitch" or "pith" rings. These are white, very narrow, and totally different in color from the rest of the wood. If they seem very soft, they have been noted as pith rings; if hard, as pitch rings. They may come either within a year's growth or between two years. They therefore are very annoying, for they destroy the count, it being impossible to tell whether the normal rings on each side belong to one year or to two. I have made it a rule to discard entirely regions of ring record thrown into doubt by such rings. Doubtless they come from injury and usually from fires. In the yellow pines no similar rings have been noted, but in each tree abnormally large rings occur close to large fire injuries during the early period of recovery and diminished rings in other parts of the tree circuit.

Effect on means—In all cases of ring errors that leave any uncertainty in dating, the uncertain part, or even the whole tree, is omitted from the means. In large groups, of course, the omission of a tree is usually a small matter, but in the early years of the group record it may be serious, for the number of individuals decreases as we go back to earlier and earlier dates. In such cases only the uncertain part is omitted. But here another difficulty is introduced, namely, the break in the averages at the beginning and end of the omitted part. If the tree in question agrees very closely with the mean of the rest in size of rings, the break does not introduce error; but if it is very different, it has to be merged with the average of the rest in some way. This becomes the same problem as that of introducing a tree of late starting-date into a long group record.

V. INSTRUMENTS AND TECHNIQUE

In dealing with the 175,000 growth-rings, dated, measured, and used in these volumes, special tools have been adopted or developed at every stage of the process to secure material and to hasten and improve results.

COLLECTING TOOLS

Saws—The articles needed in field trips include a chisel for marking numbers, paper and cloth bags for holding fragments cut from individual trees, a recording notebook, marking crayon, a shoulder-bag, camera, and various saws and borers. The best handsaw is known as a flooring saw, in which the teeth are on a curved edge of steel, as shown in Plate 2, *A*. With this, one can make a v-cut in the middle of a stump without touching the edge at all, or the saw can cut in from one side to the center without touching the other half. In working without help this has saved many hours of labor and energy. The convenient size of saw has a blade about 20 inches long. A 3-foot cross-cut saw used by lumbermen does at times prove very useful, but its extra weight and awkwardness in packing have always been against it.

Swedish increment borer—Since 1920 the Swedish increment borer has been used extensively to get records from living trees. It is very successful in softwoods such as pine and fir. Hardwoods and juniper are too tough for penetration without great danger of breaking the instrument. The cores obtained are very slender, smaller than a pencil, and reach to slight depth in large trees, but the method of mounting has been raised to such a degree of efficiency and the collection of material becomes so rapid that the deficient length and occasional worthless specimens are counterbalanced. In most regions the increment-borer material can be supplemented by a few cuts from stumps carrying the tree record back into the past as far as the forest permits. Thus the borer supplies the contemporary record, that is, the last 100 years or so from many trees, and the saw supplies the historic record going back for centuries.

In countries where native timber has been cut off and the yearly "crop" of lumber comes from planted and reforested areas, it is very important to know how growth is progressing. So Swedish ingenuity produced this tool for sampling the outer rings of a tree. The borer is a tube of 4 to 5 mm. inside diameter ($\frac{1}{6}$ to $\frac{1}{5}$ inch) with a sharp cutting-edge and prominent spiral threads to draw the tool into the tree by twisting, as with an auger. Near the cutting-edge is the largest outside diameter of the tube, about half an inch. A tubular cross-piece handle, which at the same time serves as carrying-case for the cutting-tube, gives a strong purchase in turning the borer. When the tree is bored as far as desired or practicable, a long, fine wedge is thrust into the cutting-tube from the open end outside to hold the core tightly in the cutting-tube while the borer is screwed out from the tree. The first turn, of course, breaks the core away from the tree and the core may be pulled out intact by the wedge. A difficulty with this tool is the fact that in soft and watersoaked wood the outer and softer layers are sometimes compressed and twisted. This is usually negligible, but on one occasion in a dead sequoia the water-soaked wood wedged in the borer so firmly that it had to be removed by boring another tree and thus pushing out the wedged fragments (boring in fallen sequoia at 215 feet from base of root, shown in part in figs. 1 and 2).

Core mounting—The cores usually come out intact, but gluing pieces together is so satisfactory that breakage is no drawback. The core is at once numbered in pencil every inch or two of its length, so that its pieces may be identified if it breaks. It is then put in a paper bag long enough to hold it and a full record made on the outside of the bag. Other numbered cores and their records are added in the same bag, as they help to keep each other from breaking.

These cores are mounted on half-round strips of wood 12 inches long and ¾ inch wide. A shallow saw-cut is made lengthwise at the rounded top, and this cut is rounded with a small round file so that the core will lie snugly in it. It is then glued with the bark end to the right and about 1 inch from the end of the mount. The number is placed at once on the mount at that end. In gluing, the vertical grain of the tree is turned over into a horizontal position. This gives a chance for just the right stroke with the razor blade in "shaving" the surface so that the rings are brought out into the greatest prominence. Identification and dating notes are placed on the wooden mount. The various groups of these mounted specimens are tied in bundles and filed in drawers of the proper width and depth. Such samples resist very rough handling, last indefinitely in this form, and are always ready for further study.

Mr. Duncan Dunning, of the Forest Service office at San Francisco, has made a temporary clamp of great convenience, in which the core may be held while measures of its rings are made. Considering the vast number of cores used by the Forest Service and the ease of replacing lost or injured specimens, this temporary mounting is extremely valuable.

Borer extension—The 12-inch borer is the one commonly used, giving a practical 10-inch core. A 10-inch borer was first tried and a 14-inch has been under examination, but seems too heavy. Very long borers for greater depth in the tree will probably have to be made in single pieces of tubing.

The tubular borer—This borer was designed especially for the dried and sometimes very hard logs in the prehistoric ruins. It will work on pine trees and junipers. It gives a core 1 inch in diameter, which means a better chance of finding obscure rings than in the increment-borer cores. The borer is a 1-inch steel tube with small sawteeth at one end and a projection at the other for insertion in a common brace. Collections to date include some 30 or 40 very valuable cores made with this instrument. In actual operation the core has been broken off and drawn out about every 3 inches in order to help get rid of sawdust. This extraction is done by a ¼-inch steel rod with a wedge at one end for breaking the core off and a screw at the other end to catch the core fragment and draw it out.

There are two chief problems with a borer of this sort—sawdust and the labor in pressing the borer into the tree or log. For the former a ½-inch auger hole carried below the borer hole and a little in advance has been used advantageously, but frequent breaking of the core is more certain. For the latter a chain-drill attachment was tried unsuccessfully, as it cracked the borer. An auger guide for limited depths is working extremely well in some cases. This guide is a hollow cylinder 4 inches long and 2 inches diameter, with thick walls. Lengthwise down these walls ¼-inch holes are placed fairly close to each other. This guide is screwed to the tree or log with the guide-holes pointing toward the center of the tree. Then a small auger bores into the tree through the holes in succession. The guide is then removed and the tubular borer quickly frees the core. In this arrangement the auger holes take care of the sawdust and the auger itself needs no pressure for forcing it into the wood. The core is not so presentable in appearance, but is easily rounded to a desirable form. This makes a very good form for use on prehistoric beams, but does not solve the problem of deep boring in living trees. A device using the principle of the chain-drill attachment is now under test. There is no doubt that a suitable depth borer can be developed. An effective length of 28 or 30 inches would be enough for the yellow pines. A borer to go 12 feet into big sequoias would probably have to be designed for use with an engine or motor. One would have to be sure beforehand that living trees would supply data worth the trouble.

Injury to living trees—It has been an invariable custom to plug the holes made in living trees so as to keep out any possible infection. This is easily done with a small branch from the same tree, cutting the bark entirely away, so that only healthy sapwood goes into the hole. This amounts to grafting a young branch onto the trunk. Even without this precaution it is not probable that any harm results, as the holes quickly fill with sap or pitch.

Razor-blade holder—In giving a final superb finish to the wood surface, nothing has been found to replace the razor-blade. Files, emery cloth, and scrapers always leave the edges of the wood cells in a ragged state. This may be overcome to some extent with kerosene, oil, or furniture polish, but after clean cutting with a sharp razor-blade the oil finish is far superior. Also, in decayed or burnt wood, after treatment with paraffin, the razor leaves a surface which will permit adequate magnification. Different forms of mounts could easily be made, but a round steel handle split down an inch with a hack-saw and a good screw to draw the split ends together serves as a very convenient mount for the safety-razor blade.

Paraffin treatment—Soft or mealy wood or charcoal is rendered workable by a treatment with paraffin dissolved in gasoline or benzine. This solution should be applied copiously, so that it may enter deeply before it dries. Putting the whole specimen into a jar containing the solution has been found very satisfactory where practicable. Boiling a frail specimen in paraffin is an excellent method of preservation to apply while out in the field.

MEASURING INSTRUMENTS

EARLY FORMS

Ruler—As would be expected, the first measures were made by readings from a steel ruler on edge against the wood. These measures were all made by the writer and were subject to the errors of estimating tenths of a millimeter, but in coarse rings such errors play very little part.

Cathetometer method—This method was worked out for the very long sequoia records and is still regarded as the standard method. It was described in Volume I and need not be repeated here.

PLOTTING MICROMETER

It seemed possible to save a large amount of time by some method of plotting direct from the wood and a special instrument has been designed and constructed for the purpose.

General plan—In general plan the instrument has a fairly inexpensive screw, 6 inches long by about 1 cm. in diameter, with threads having a pitch of 1 mm. A knurled head and a graduated head are attached at the right end for turning and for special reading if desired, but the graduations have not been used (see Plate 5).

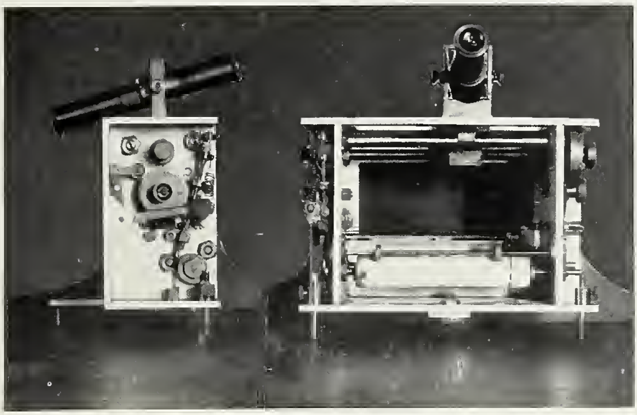
The nut on this screw, by a single point of contact, moves a carriage supported on a separate track. The carriage has two upright pieces, between which a small telescope swings on a horizontal longitudinal axis. The left end of the main screw opposite the graduated head has a knurled head which is removable. Below this head, but not in contact, is a similar head, also removable. The latter is attached to a small drum with spiral thread about it, in which works a catgut string. Between these two knurled heads, but not touching them, is an aluminum disk on the end of an arm, so made that by pressure on a lever the disk comes into contact with both these knurled heads and thus transmits the motion from one to the other and so from the main screw to the catgut string. Several pairs of these knurled heads of different relative sizes are supplied, so that motion in the catgut will be 20, 40, or 100 times the motion of the carriage and telescope. By this means change may be made in the vertical scale of the plot.

Below the main screw and parallel to it is the plotting cylinder. This is so arranged that the same lever-arm that brings contact between the knurled heads moves this cylinder 2 mm. in rotation, measured on the surface of the record paper. The ends of the catgut string pass over rollers and extend parallel to the recording cylinder, and after one end turns back on a small wheel the two ends meet and are attached to the pen carriage, which travels on its own track parallel to the recording cylinder. Thus, when the lever-arm is pressed and the micrometer screw moves the telescope thread across a ring, from one sharp outer edge to the next, the pen draws a line in proportion transversely on the record sheet. The release of the lever-arm at the left moves the cylinder, and the pen is restored to zero position. Thus a columnar plot, here called "auto-plot", is made by setting on one ring after another.

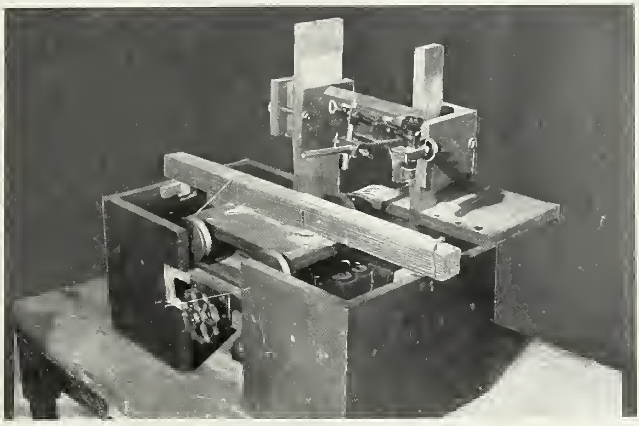
Accuracy—The rapidity and mechanical accuracy of this instrument are high. The graduations of a steel ruler were measured with a very small percentage of error; that is, the accuracy is greater than the accuracy of setting on a ring.

Advantages—The instrument saves much time, because it makes automatically the plotted records which in the cathetometer method were plotted from the readings. These automatic records are called auto-plots. The distance of the wood from the telescope does not have to be fixed. In fact, I have measured rings in wood lying in glass cases by placing the instrument on the outside of the case. The records are in a convenient form and may be very long. They are made on coördinate paper to definite scale, so that values may be read off from the plots for use in tabulation. The plot is also ready at once for a standardizing line, such as will be discussed below.

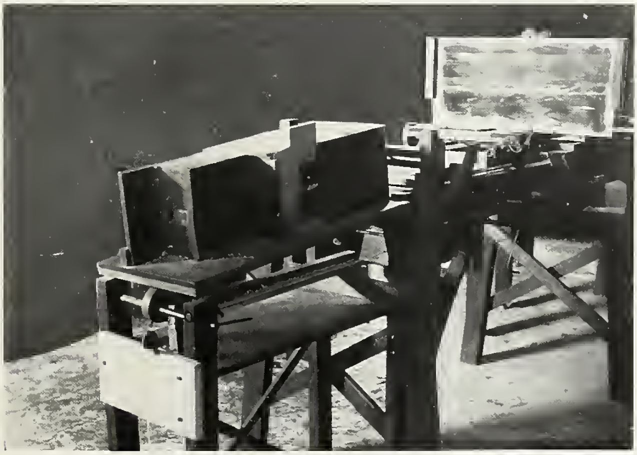
Disadvantages—While the rapidity and accuracy of this method exceed any other, its disadvantage lies in the difficulty of checking and correcting the work after it is done. Coarse rings are readily handled by inexperienced helpers, but the fine ones under 0.5 millimeter are subject to mistakes. This is usually a question of identification, but the difficulty in checking work immediately after it is done (without



A. Plotting micrometer



B. Longitudinal plotter



C. White cyclograph

doing it completely a second time) is great, and so these errors of identity are not discovered until a careful revision is made by the writer. All this refers, of course, to the measurement of records carefully dated beforehand.

Measuring directions—The best plan for preventing errors in measuring is a written set of measuring directions, telling where to begin and end, what rings, if any, to omit, which are small or microscopic or absent, and where dangerous doubles occur. When a radial sample is specially illuminated during measuring in order to see the rings well in a telescope, marks and directions on the sample may easily be overlooked, but a separate list on a paper at the side can be followed with greater success.

Other applications—Extensive experience with the ordinary filar micrometer in astronomical work led to a design of this instrument which could be used on a telescope for the repeated measurement of the same distance, such as planetary diameters, separation of double stars, and so forth. The box of the plotter was arranged to receive on one side a bushing adapted to the slide-tube of a big telescope and on the other a positive eyepiece. Close to the eyepiece is a plate carrying a stationary thread, while another plate attached to the carriage has the movable thread. The latter is first placed on the left side of the planetary disk and the stationary thread on the right. Then the lever-arm above described is pressed and the movable thread carried to the right until it reaches the right edge of the disk when the other is at the left edge. Thus the double diameter is measured. This may be repeated as many times as desired before looking at the record. A thread stretched along the tops of the columns will give the mean value. This same method can be used in the measurement of average seed diameters under the microscope or the sizes of grains of sand or other objects under special study.

LONGITUDINAL PLOTTER

The measuring instruments so far described all require accurate dating beforehand, for corrections are hard to enter after the ordinary transverse plot has once been made. It happened that considerable material came to the laboratory with groups of very small rings which I did not have time to date, but at a time when there was available the help of an assistant. It was therefore desirable for him to put on a ring-count and make measures which I could correct at my leisure. This was accomplished by the longitudinal plotter (Plate 5, *B*). It simply reproduces the spacings which exist on the wood on a large scale that can be varied to suit the needs of the rings. It reproduces very rapidly and two independent records are placed side by side on the long paper tape such as is used in adding machines. This is called the longitudinal plot, or more briefly, the "long-plot." The instrument consists simply of a slow-moving carriage on which lies the wood sample and a fast-moving drum upon which hangs the recording tape. These are connected by gearing which normally permits the surface of the drum to move 12 times as fast as the carriage. A pair of gears may be removed and another pair substituted, giving different ratios, so that the range of magnification is from about 4 to about 34 times. In this way a convenient size is entered on the recording tape and the record becomes partially standardized. The motion of the carriage and specimen is watched through a small stationary telescope placed a few inches above and focussed upon the rings and the motion of the drum is recorded on the tape by a pencil line drawn across it against a fixed wire.

Accuracy—On the whole, an inexperienced assistant can handle this plotter better than any other form of measuring instrument. The duplicate records side by side check each other nicely. It is still subject to errors of identification, but a large quantity of dated specimens have gone through this process with good success. It is doubtful if the settings have been quite as accurate as in the auto-plot, but they are still as good as the sharpness of the rings permits.

Graph and table—A sheet of coördinate paper is marked with dates and then each ordinate is entered simply as the sum of the lengths of that year in the two adjacent longitudinal plots. This gives an ordinary graph on which a standardizing line may be drawn, as described below. Suitable ring values for entering in a group table are then read off directly from the graph.

CLERICAL OPERATIONS

STANDARDIZING

Need of equalizing trees—The groups of trees used in this study represent different regions. Therefore, the individuals of each group were selected to represent a considerable area rather than a localized spot. Hence the individuals differ in rate of growth. What we want in an average of a group is the common character which has come from climatic variation. In the tables in Volume I a simple average was used, as that was the easiest process and commonly used in scientific reports. But it is perfectly evident that a straight average does not represent an average of the common character, because in ordinary averaging the big rings in quick-growing trees dominate and variations in the slow-growing trees are practically lost. Logarithmic averaging has been considered; for example, multiplying the values from the different trees together and extracting the root corresponding to the number of trees used. But that is a long and expensive process, and it renders serious the occasional microscopic or omitted ring in very slow growing trees. The effect in such cases would be greatly over-done. So the practical method of standardizing or equalizing trees, which has been used extensively for actual curve production (commonly modified as in the next paragraph), is to divide individual values by the mean value of the tree, so that the annual values of each tree will enter the group table as percentage departures from its own mean. Simple averages are then taken for each year in the group. This avoids some of the exaggerated effect of extreme departures. It places all the trees on an equality, but does not place all departures on an equality. It is averaging by weight, in which the weight is inversely proportional to the mean growth of the tree.

Age correction—Young trees have to develop the trunk rapidly in order to stand the strain of wind and snow. Hence the early rings are larger and somewhat less sensitive to climatic effects. When the tree curve is plotted, it usually rises at the early end, sometimes very rapidly. A reduction to percentage departures does not correct this. One can correct it by getting percentage departures from a type curve developed mathematically, as Huntington did (1914), but it can be done far more rapidly and with sufficient accuracy by drawing a curved or broken standardizing line on the individual plot and getting the percentage departures from this line. Such a line is usually straight and horizontal for a large part of the record and slants upward at the early end. A curve is more accurate than a broken line, but there is little real difference and the broken line is more easily described if it is necessary to state its position in words.

Other corrections—Huntington used a "flaring" correction for the increased measured width of outer rings near the base of the big trees, where the spread of the root system is felt and a horizontal measurement is not perpendicular to the rings. Evidently, in drawing a standardizing line this can be taken care of. It is evident that in studies of cycles not exceeding half a century or so in length the flaring effect is negligible. But in estimates of very long periods or of secular values, this effect must be nicely gauged.

It is much the same with his "longevity" effect. This effect simply recognizes that a slow-growing tree has a different normal age-curve from a quick-growing tree. The slow grower more quickly reaches the normal slow growth. This, too, is important in getting early absolute ring values, but plays little part in studies of periodic variation.

Comment on standardizing—It is felt that standardizing serves two purposes: first, correction for age, injury and flare, and second, it compensates for few numbers in a group, so that 5 or 10 trees will give practically the same results as 25 or 100. It is not thought important to use it if the number of trees used in a group average is over 15 and the age variations are small.

Averaging—The sums are usually made on an adding machine and the divisions by slide-rule. Once or twice an average by weight has been made. If some character is recognized that makes the record in one tree better than that in another, a suitable weight can be included in the standardizing process by placing the standardizing line at a different ordinate. In the table the same effect has been produced by repeating the same tree in two or more lines, giving it double or more weight.

CYCLE PLOTS

Uses of tree-growth curves—There are three main purposes in producing tree-record curves and certain advantageous characters vary in these uses. They follow.

Cross-identification—Curves for this purpose must display certain special characters like single small rings or drought groups of small rings, which from their extreme and unusual character are likely to extend over a considerable district. The single small deficient ring is the best characteristic to use in dating. Good years seem to spread their effects over a longer period of time and are not definite.

Skeleton plot—In consequence, a special "skeleton" curve has sometimes been successfully used in cross-dating. Such curve is a long, narrow strip of coördinate paper, dated or numbered as usual and showing only the dates of very small microscopic or absent rings, which are indicated by vertical lines whose conspicuousness is proportional to the deficiency of the rings. No other rings are represented in these plots. Two of these skeleton curves from different trees, one known and the other unknown as to date, can be moved slowly past each other until similarity of spacing discloses identity in dates.

Plotting climatic curves—By comparison of growth-curves the climatic origin of many tree variations is established; hence these curves need to show all the individual years. The scale should not be too great, as then it is difficult to compare two plots. Therefore, the ordinary form, consisting of points connected by straight lines, made on such a scale that slopes dominate, is the more convenient. It has been found most advantageous to use coördinate paper whose smallest divisions are 2 mm. and whose major lines are spaced at 5 (not 10) of these small divisions. On this paper the smallest horizontal division commonly represents one year and rather commonly 2 vertical centimeters represent 1 mm. of tree-growth.

Cycle plots—These are the curves arranged specially for studying the cycles. At first it was thought that the usual unsmoothed plots just described were well adapted for this purpose, but it was noticed that in searching out some cycle with the periodograph, or cyclograph as it will usually be called in this volume, several possible settings were obtained differing by exactly one year, such as 17.1, 18.1, and 19.1 years. This, of course, arose from retaining annual points in the plot and in the cycle one was apt to select some multiple of unity, that is, simply a whole number or very close to it, instead of an actual fractional value.

Smoothing—Accordingly, some form of smoothing is now always used, and the Bloxam formula, which I have sometimes called Hann's formula, is generally accepted. But there are several variations of this process.

Numerical Hann—The first is the simple application of the Hann or Bloxam formula, in which three successive (overlapping) values are merged into a substitute for the middle one by averaging the three, with double weight given to the second. It is this double weight applied to the original whose substitute is desired that differentiates this formula from a running mean of three. The place of this emphasis will be referred to below. This process may be done on a set of tabulated values by two successive sets of intermediates, as explained in a previous volume.

Geometric Hann—This is the same process, done graphically on a curve already plotted, by taking each three successive points as the corners of a triangle. Consider that the first and third points form the base. From the center of the base, one-third of the way to the middle point will be the running mean of three, while one-half of the way from the base to the middle point will be the weighted mean or the "Hanned" value. This forms in practice a very easy way of smoothing a curve and has been very largely used in a slightly abbreviated form which I have called the graphic Hann.

Graphic Hann—The plotting paper used in the cyclograph needs to be 4 inches wide by some 45 inches long, fairly opaque, and with parts of the curve cut out so that light may pass through. All this is best done on rough brown paper cut in strips of the proper size. The present process, therefore, is to plot the tabular averages directly on a long strip of coördinate paper, using a rather large vertical scale, so that variations will generally be an inch or two high. This strip is placed upon the heavy strip of brown paper with carbon paper between and a blunted needle or pointer is passed slowly along the plotted curve, touching the points which by eye estimation and occasional measure should constitute the geometric Hann. Century dates at the same time are touched, so that the curve thus transferred becomes a satisfactory working smoothed plot of the standardized group average. This is called the graphic Hann and can be done quickly and accurately. This process of smoothing has a perfectly definite ideal to look to in case of doubt and I believe is almost entirely free from erratic estimations, on account of which ordinary eye-smoothing may be criticized. The graphic Hann thus formed is the basis of the cycle plot whose process of formation will be continued below.

Emphasis point—In the Hanning process just described the emphasis is laid on the middle point of the three. This has been used in so large a part of this curve-production that it is here given preference. But there is some question about its use when conservation is considered, for it intimates a reversed or negative conservation in the last year of the three (see p. 101). If rainfall is retroactive, that is, if it affects rings already formed, the tree records ought to show some anticipation of abrupt changes in the rainfall. On the other hand, placing the emphasis on the last of the three years used amounts to admitting a conservation of moisture from the two preceding years. On the whole, it is felt that middle-point emphasis has given more satisfactory curves than emphasis on the final year.

Cutting-line—The cycle plot has the maxima of the curve cut out so that light may pass through. The curve produced by the graphic Hann forms the upper side of this area to be cut, but the position of the base of the cut area has proved very important in the successful use of the analyzing instrument and therefore I have always had the curves at that stage returned to me to have the base or "cutting-line" marked. In any analysis the variations of the curve are the important features; hence, if the cutting-line is placed along the X-axis or the true base of the curve, the variations are reduced to very small percentages of the total light coming through and can not be seen. Even when the cutting-line is placed at the lower minima, the light is so abundant that it is very hard to get the variations visually or photographically. After extensive trials of every sort of height for this line, I have come to the general plan of sacrificing about one-third of the vertical height at the bottom of the minima and marking a long, sweeping line nearly straight, but not entirely so, as that brings the best display of variations within the range of the instrument and has not been found to affect the results.

The range of the instrument as now in use is confined to periods between 6 and 32 years (see "Recent changes," below). The cutting-line, therefore, to show these best, may be curved so as to cut out or reduce longer periods. They, however, are taken care of by plotting at a reduced scale. This has been done extensively with long sequence of rings extending 500 years or more.

Cutting the plots—The final work on the cycle plots is cutting out the maxima, which, of course, is a simple matter usually done with a razor blade.

THE CYCLOGRAPH (PERIODOGRAPH)

COMPARISON OF ANALYZING METHODS

This study of tree-rings has become a study of the history of climatic cycles. The technique so far described covers the production of tree-record curves ready for analysis by a special instrument designed for the purpose and called a cyclograph. The number of curves to be analyzed is so great and the data sought so complex that this work would hardly have been done by a mathematical process. Harmonic analysis in its mathematical form has been so successful in numberless studies that many investigators have come to regard it as essential. A very clever illustration of its power is Miller's reduction of a facial contour to a mathematical formula which when plotted reproduces the contour. Of course, this was done by combining a long descending scale of period lengths with the distribution of emphasis (amplitudes) on just the right ones. But after this beautiful illustration we must not forget that this form of contour analysis has nothing to do with the physical causes of the contour, nor does it help us in predicting other contours. It is like a photographic plate: it merely places that one on record.

So in the case of the sunspot cycle, we can reproduce the known historic sunspot curve by 20 harmonics with different amplitudes, but when done we can not insist that the sunspot variation is really built of those harmonics. So also with climatic cycles, we do not know yet how far their physical causes are harmonic, and therefore the expression of climatic variations in a Fourier series begs the question. Evidence in a later chapter suggests distinctly that climatic cycles are simple fractions rather than harmonics of a fundamental. So the photometric process described below is permissible. Add to this its rapidity, which is of the order of 50 times as great as the mathematical process, while its flexibility belongs to a different class altogether. The mathematical process is not flexible at all in the sense this is. The process here used bears somewhat the relation to the mathematical process that calculus does to algebra; it is differential. In applying a cycle to a long sequence of values, one sees at once at every point how far the values depart from the cycle. A varying cycle enters simply as a curved line, while a fixed period appears as a straight one. Two interfering cycles, forming a false third, enter as two straight lines or bands intersecting and their intersections form the third. In this process the operator not merely gets an analysis of the whole sequence of values, but of every possible fraction of them, an accomplishment of the highest difficulty in any mathematical solution. For example, Schuster analyzed the sunspot variations since 1750, dividing the whole series into two parts, and missed the points of discontinuity near 1788, 1830, and so forth. These discontinuous points are the most conspicuous features of the cyclograph analysis here used.

On the other hand, some will object, and correctly, that the cyclograph process does not give in figures the harmonic constants. Two points answer this; the first is that the cycle must first be caught out of a very complex combination of variables, and second, when the cycle is known it is easy to get its constants by mathematics, if desired (or by photometric means from a cyclogram).

PRINCIPLE OF THE CYCLOGRAPH

The earlier forms of the instrument have been described in the previous volume and need no repetition. The principle also was explained, and is briefly outlined here only as an introduction to the present form. The maxima of the curve to be analyzed are cut out, so that light passes through in proportion to the ordinates, as already described under the title Cycle plots. The horizontal spacing of the maxima of light is emphasized if the cutting-line is high, leaving the extreme minima without illumination. Now let us imagine a plot of this sort consisting of a series of evident maxima which seem to be equally spaced (as in the sunspot curve), and we wish to find if they are strictly periodic. We illuminate the curve from the back, place a lens at some distance before it, find the image cast by the lens, and compare the white spots in the image with an adjacent series of dots which we have placed on exactly equal spaces. If the dots are closer than the maxima, the lens is carried farther from the curve, reducing the separation of the focal images until they coincide in the average with the equally spaced dots. Then we see clearly that the maxima largely match the dots but in certain places; let us say, they draw away. These departures let us call differentials.

So long as differentials take place in their own line (like the longitudinal vibrations of sound) it is hard to estimate them, but if these differentials can be turned out perpendicular to the line of the curve, that is, made transverse (like light-waves), it is very easy to see and measure them. This is very easily done by extending both maxima and dots indefinitely in the transverse direction but at a small angle to each other. This effect is produced on the curve image by adding a cylindrical lens which converts each maximum of the focal image into a vertical band. The same effect is produced on the dots by inserting in their place a series of equally spaced nearly vertical opaque parallel lines. To give these lines accurately, a ruled screen such as that used in photo-engraving is placed at the focus of the lens and the row of vertical bands comes through the slightly inclined transparent spaces between the lines. This produces an interference which should be seen to be appreciated. If the maxima are equally spaced, they come through as straight horizontal rows of white spots, but where differentials occur, the spots are displaced above or below the straight line. Departures from a perfect period are at once recognized, because longitudinal displacement has been turned to transverse, thus making a departure from a straight line which is at once apparent.

Invention and name—This pattern was first designed by the writer in 1913 and published in 1914 under the name of a multiple plot.* Its automatic production by this method of interference was worked out that same year and published in 1915. It was then called a differential pattern and was used as the basis from which to photograph a true periodogram, as described in Volume I. In the present volume, however, the periodogram is omitted, since there has been very little use for it in comparison with the pattern. With the construction of small portable instruments for producing this pattern, the word cycloscope has come into use as their name. In a corresponding way the large analyzing instrument with its photographic attachment, constructed with the fund given by Mr. Clarence G. White, of Redlands, California, has come to be called the White cyclograph; the photographs obtained by it are here called cyclograms.

THE WHITE CYCLOGRAPH

During the building of the previous instrument in 1918 the thought in mind was the production of a periodogram as suggested by Schuster. But with the extensive use of that instrument it became apparent that the differential pattern or cyclogram designed as merely one stage in the process was far more important than the periodogram. The periodogram merely produces the kind of results that come from a mathematical process; the cyclogram contains far more than that.

At the same time, the long track of the periodograph compelled the observer to walk indefinitely back and forth in an awkward position. So it was first intended to arrange a mechanism to eliminate this walking, but as it took form the lessening importance of the periodogram was realized and the attachment for producing it was omitted. It could, however, be added at any time if thought worth while.

Illuminator—The arrangement for mounting the cycle plot so that light comes through in the proper way is called the illuminator. For a long time daylight was used, thrown onto the curve in a darkened room by a slant mirror at the base of a window. Then thin white tracing-paper replaced the mirror and gave a broad area for comparing different curves. One curve some 40 inches long and 4 wide was insufficient and a second could be put above it. But for close comparison of many curves for dating purposes a light frame sliding vertically was arranged to carry 10 curves at once. This frame was suspended by a cord over a pulley and analysis could pass from one curve to another at any desired speed.

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*It appears to be identical with Clayton's "phasogram" in World Weather, page 379. The multiple-plot method of making a periodogram was described to him in conversation in the summer of 1913, and he remarked, "Well, you might expect an astronomer to work out an optical method."

When it became necessary to move the instrument to a locality where a suitable window was not available, 10 electric lights in a row were used, with a mirror behind and several thicknesses of ground glass between the lights and the curve to spread the light evenly. This is mounted on a table or stand, but it is planned to combine all this equipment with an attachment which will permit the curve to turn on its center through a horizontal angle, for by this means the range of analysis can be greatly extended beyond the previous 32 years. This slanting of the curve can only be done when it is at maximum distance from the lens, for the two ends would come in at obviously different scales. To do this the whole illuminator will have to turn on a central vertical axis.

Track and carriage—The cyclograph track is 18 feet long (see Plate 5, *C*), made of light beams well braced, carrying cross-pieces, notched at each end to hold two lengths of ½-inch round steel shafting which serve as rails. The rails are 18 inches apart. The carriage has two grooved wheels on one side to run on one rail and hold the alignment. On the other side is a single flat wheel.* The carriage holds a vertical mirror 30 inches wide and 15 inches high, facing the illuminator and the analyzing-box. Seen from the mirror, the former appears slightly, but directly, above the latter. The carriage is moved by a cord passing over a small wheel at the outer end and a drum with small spiral groove about it at the observer's end. This drum has a handle within reach of the observer as he sits at the side of the analyzing camera.

Scale—The scale runs along the side of the track and the carriage has a mirror and light so arranged that the observer may see the lighted scale at any position of the carriage. A small telescope is provided for reading the distant positions. The graduation is put on from standardized curves, which are always kept on hand and measured and tried from time to time. In dry climates all curves shrink perceptibly and thus scales have to be watched.

Range extension—The actual length of the track covers a range of periods from 5 to 18 years. In order to increase this to 32 years, two mirrors have been used, one fixed high above the track, throwing a beam back toward the analyzing-box, and the other at the front of the box in this beam, so placed that when it is raised in position it catches the beam from the first extra mirror and sends it to the mirror on the carriage, at the same time cutting off the direct light from the curve to the carriage. This nearly doubles the maximum path of the light from the curve to the analyzing-box and increases the range of periods tested from 18 years to over 32 years.

Camera inclination—One bit of awkwardness remains in this design, namely, the necessary change of slant of the camera-box when the movable mirror is changed in distance. In order to get the reflection from the mirror properly placed, the box has to have its plate end lowered when the mirror comes near.

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*This same carriage was used on September 10, 1923, in photographing the total solar eclipse from the University of Arizona station at Port Libertad, Sonora, Mexico, with a 40-foot horizontal telescope.

Cyclograph camera—By the track-and-mirror arrangement, above described, the observer can stay at one point while the moving mirror changes the effective distance between the curve and the lens, and by changing the size of the focal image brings into view all the range of periods of which the instrument is capable.

Lens.—The lens is a Tessar II B of 6 inches focus and about $\frac{3}{4}$-inch aperture, with a negative cylindrical simple lens of -6 inches focus with horizontal axis, so that in the vertical direction it neutralizes the action of the main lens. Without the cylinder there is an ordinary image at 6 inches. With the cylinder all the horizontal spacing comes in as before, but there is no vertical focussing; consequently, each maximum in the curve appears in the image as a vertical band whose intensity is proportional to the height of the maximum.

Automatic focus—The lens is mounted as in previous instruments inside and on the base of a suspended parallelogram with hinges at each angle. The length of the parallelogram extends along the axis of the instrument, in line with the track. This permits a focussing motion of the lens in its axial line. From the front of the parallelogram a lever-arm extends downward and is attached by an adjusting-screw to a horizontal rod passing forward toward the axis of the drum which moves the mirror-carriage. A cross-piece on the rod bears against a brass spiral mounted near the axis of the drum and turning with it. This spiral is so arranged that as the drum turns, the position of the lens changes and the focus is maintained in a fixed plane.

Analyzing-plate—The analyzing-plate is fixed at the focus of the lens in a brass mounting attached to the back of this front compartment of the analyzing-box. The mounting has been elaborate enough to test many details and is rather more complete than ordinarily needed. On the fixed plate is a circular brass plate which can be rotated through 45° against a graduation in degrees. A rectangle 1 inch high and 2 inches long is cut through the circular plate, and on this rectangle is mounted the analyzing-plate, covering a little more than the rectangle. The ruled lines of the plate are vertical, that is, parallel to the short side of the rectangle. In normal position the circle is clamped so that the lines are inclined 12° from the vertical, and therefore 12° from the vertical bands in the image.

The plate itself is made of two screens accurately ruled 50 lines to the inch, face to face, one fixed and the other with a slight motion controlled by a screw. The purpose of this is to change the relative size of the transparent part of the ruling without changing the distance from center to center of the lines. In each screen the opaque ruling is equal in width to the transparent space between. So by moving one screen slightly across the other, the transparent part can be changed from zero up to 0.01 inch. The width found advantageous is 0.004 inch or two-tenths of the spacing of the lines.

Visual compartment—From the analyzing-plate the light passes into the middle or visual compartment through the condensing-lenses. These are two 6-inch positive cylindrical lenses with vertical axis, so that the eye placed 6 inches away may receive all the light from the plate and see its whole area. It is more convenient to have the observer at the side than at the end, where he may interfere with the light coming from the curve beyond, so back of the condensers is a vertical mirror on a hinged support. When the support is pulled forward, it takes a position at 45° and throws the beam out at the side through a small lens and to the eye. The lens puts the image slightly out of focus to the eye, as in such condition the eye recognizes alignments of blotches better.

Photographic compartment—When the mirror-support is thrown back out of the way, the beam goes straight on to a triple lens of 3 inches focus, which reproduces the analyzing pattern on a ground glass in the third and last compartment. This last compartment is held separate on a clamp by which the ground glass may be brought to the most advantageous focus. A plate-holder fits in place of the glass and may occupy three slightly different positions, so that three exposures can be made on the same plate.

Recent changes—The above description gives the form of the instrument used in the cycle analyses in this volume. But since writing this chapter added floor-space has made it possible to lengthen the track to 40 feet. With this the two extra mirrors have been removed, together with the automatic focussing device and scale illumination, and a small convenient scale is now located directly in front of the observer.

CYCLOSCOPE

A small portable analyzer has been constructed for exhibit purposes, but fully equal to real analyzing work. It consists of a small illuminator with a long electric light inclosed and cord to be attached to a wall-socket. Curves 10 inches long may be placed in this. The analyzing part is a box 12 inches long and 4 inches square, with top which opens on a hinge. It carries a convex spherical and a cylindrical lens at the front, with a little chance to focus by hand; then a simple analyzing-plate fixed at the proper inclination; then condensing-lenses and an eye-lens. One looks through it toward the illuminated curve and walks nearer or farther and watches the changing pattern. When a cycle is indicated by proper horizontal alignment of spots in the analyzing pattern, its value may be found by a simple formula after measuring the distance from the lens to the illuminated curve.

VI. TREE RECORDS: LENGTH

The first definite purpose in making the collections here described was the extension and improvement of the 3,000-year sequoia records presented in the previous volume. This was followed by a similar plan in regard to the yellow pine as soon as certain probabilities of extension were realized. The present chapter deals with these attempts. As the number of specimens grew and material came from many sources, the study of local and continental topographic effects took shape and has become a central theme of this volume, as indicated in the succeeding chapters (VII and VIII). Finally, large quantities of early historic, prehistoric, and geologic material came to the laboratory and the problem was presented of reconstructing, in part at least, the climates of past ages by such indications as could be found in tree-rings. Hence arose the thought of collecting and formulating climatic indicators in trees (VIII). All this is of fundamental importance in the continued investigation of climatic cycles and tree-growth (IX).

OLD SEQUOIA RECORDS

THIRD SEQUOIA TRIP, 1919

The trip to the groves near General Grant Park in July 1919 was made for the purpose of determining the status of a certain ring called 1580A, which was in doubt because it had appeared in less than half of the 23 specimens at that time in hand. It was also planned to make a topographic study of the influence of the immediate environment, especially ground-water, on ring-growth. After a trip to Wigger's, just south of the Park, to see an immense stump, and after an examination of the General Grant tree to estimate its age, I went to Hume and on the 12th accompanied a guide to the farthest parts of Camp 6, where Nos. 1 to 5 had been collected, and selected new specimens for cutting. The next day, with burros and a helper, camp was made at the mouth of Redwood Basin, near the spring. With no one to help, the radial pieces cut here the next morning were not on the scale previously obtained. Instead of being 6 or 8 inches wide and deep, they were about an inch in those dimensions. This meant their breaking into many small pieces, which were immediately put into small marked bags. The new specimens supplemented the 13 already obtained in that district and gave opportunity of testing more thoroughly the relation of sequoia growth to ground-water, which will be discussed in a later chapter.

The next day we cut a new radial from D–12 in Indian Basin, which had previously failed to give a satisfactory dating on account of badly compressed rings near the outside. A good radius was selected and a conspicuous ring was traced across from the new radius to the old and its position on the old accurately determined. It proved very easy to extend the dating on the new radius back to this ring, and with this good start the entire dating of this tree proved very satisfactory, in spite of the complacency of its growth.

We returned to the Park and the next day I cut radials 32 to 35 at Converse Hoist. These supplemented the two obtained the year before in that vicinity by going higher up on the ridges for Nos. 32 and 35 and nearer the creek for 33 and 34.

This locality is a very interesting one, because it contains the stump D–21, which had 3,200 rings in it, whose central rings were shown in Plate 1. Very old trees are rare. I have examined many hundreds of stumps, made estimates of their age, and in many cases have counted the rings. There were in these forests many trees over 2,000 years of age, but probably very few over 3,000. Only 3 stumps of this age are known so far. Two estimates of the General Grant tree gave 2,000 and 3,000 years of age, and its true age is thus taken as 2,500 until some better opportunity comes for getting its number of rings. The Centennial stump nearby was estimated to have some 1,800 rings and the large stump with raised center at Wigger's probably is 1,500 years of age.

FOURTH SEQUOIA TRIP, 1924

The fourth sequoia trip in July 1924 had two objectives; first, the improvement of the general sequoia record, and second, the securing of certain indicators needed in the problem of correctly dating large numbers of prehistoric tree-sections from the ancient ruins of the Southwest. Such dating would not only help the archæologist, but at one stroke would also extend the superb yellow-pine climatic record by more than 300 years at least. The general problem of dating unknown tree-records will be taken up at another time. It is sufficient to say here that one way to accomplish such dating is by cross-identification between the pines of the Arizona region and the sequoias of California. This apparently would be easy by comparison of the occasional common deficient years, perhaps eight per century, except that in about one-fourth of such cases the Arizona deficient year occurs one year late. For example, the small sequoia rings for 1846, 1812, 1541, and other years in California come in 1847, 1813, 1542, and so forth, in Arizona. The attempt is, therefore, now being made to discover in the pines or sequoias, or both, some internal signs by which to know just when this difference of one year is to be expected. Hence, in approaching this problem from the sequoia point of view, it seemed best to go to other sequoia groves and see if some indication of this occasional discrepancy could be discovered.

Accordingly, a trip to the northerly Calaveras Grove was made in early July 1924, by stage from Stockton. This grove was the first one discovered and the marble slabs with tree names are reminiscent of the pioneer days. The hotel is picturesquely situated at the edge of the grove and nearby is the Dance Hall mentioned by Mark Twain. This hall is on the stump of the first big tree cut (1853) and the early difficulty in penetrating such immense trunks is apparent, for in this case it was done by large auger-holes made on opposite sides toward a selected diameter. These holes show in the great butt-log still lying close to the hall. This tree was quick-growing and estimated to have some 1,200 or 1,400 rings only. It was probably the one from which a tracing of the whole set of rings was made about 1865.

The road, as it approaches the hotel, formerly passed between the "Sentinels," two fine sequoias, but one had fallen the previous year and a boring in it at some 50 feet from the original ground-level, checked by a similar boring from another fallen tree, gave a perfect start in dating the trees in this grove. This actual dating, however, proved unnecessary, for it was perfectly easy to date all the records obtained by comparison with the known records in the more southerly groves. The trees in this grove are standing and, therefore, it was difficult to get any satisfactory radials. However, a very few old trees had fallen and small pieces were cut from three in inconspicuous places by which the record was carried back some seven centuries. Incidentally, this dating of fallen trees gave excellent data on the durability of sequoia bark and sapwood already referred to.

This grove is small, perhaps one-third of a mile across, and lies in a flattish, slightly depressed area with drainage to the southwest and protected on the other sides by hills and ridges a few hundred feet high. Its elevation is 5,000 feet and the precipitation in this neighborhood is probably near 40 inches, mostly in winter. The ring-growth is very complacent, with deficient rings showing but rarely. The average size is smaller than expected. The easy cross-identification with the tree records in the other groves shows that the entire area of *Sequoia gigantea* in California is essentially a unit in its climatic reaction.

A full day was given to collecting yellow-pine borings in connection with the study of modern tree-records over the whole western area. Trees were selected in an east-and-west line across the grove from the hilltop back of the hotel to the ridge on the east, where the main highway passes and the trail to the South Grove branches off. These pines cross-identify well and are included in the western groups under the abbreviation CVP. Eleven trees comprise this close group, but three more were added at elevations nearly 2,000 feet above sea-level in the vicinity of Murpheys. These three, however, give essentially the same record as those near the grove and are included in the CVP group. The Calaveras Grove of sequoias is privately owned and these specimens were obtained by courtesy of Mrs. Whitesides, in charge at the hotel.

FIFTH SEQUOIA TRIP, 1925

The dating of the specimens from the Calaveras Grove led to the conclusion that the tree-records there resemble the Arizona pine-tree records less than the sequoias farther south, instead of more. So it only remained to visit the most southerly grove near Springville and secure better material than already collected there. In 1918, two 3,000-year old radials had been secured from the Old Enterprise mill-site. These both cross-identified with trees 50 miles north near the General Grant Park, but while the cross-dating was absolutely reliable, the resemblances were not so close as hoped for and were not equally good in the two trees. No. 23, age 3,100 years and growing near the drainage brook, showed less agreement than No. 22, age 3,000 years, growing near the center of the grove. Accordingly, the trip was made by auto from Pasadena to Springville on August 4, 1925. Mr. Charles A. Elster, of that city, met us and next day took us to his Camp Lookout and sawmill in the pines at an elevation of about 5,000 feet above sea-level. After lunch he drove us up the steep grades, past the old Frazier mill-site of 1885 and the Elster mill-site of 1901, to the Enterprise site of 1898. The Conley mill of 1892 at Brownie Meadow, off the road to the north, was close to D–49, which had been cut by Mr. Elster himself in 1892. Mr. Elster had worked here in the lumber business almost since its beginning and his recollections were of the greatest help. The afternoon was devoted entirely to the selection of suitable stumps for cutting. It seemed advisable to get the very oldest and, if possible, to exceed the previous maximum of 3,200 years (but that hope was disappointed). At the same time it was desired to get a range of younger trees in order to develop an improved system of age corrections.

The next day the cutting of radials began. This was done by two helpers in charge of Mr. P. W. Weirick, of Pasadena, who very kindly assisted me on this trip, thus enabling me to spend the entire time in the selection of specimens. So two days were spent in this way and in securing specimens of pine growth (see p. 88), and on Saturday, the 8th, Mr. Elster took us to Balch's Park to see the marvelous old tree appropriately named Methuselah. That afternoon we returned to Springville and the next day to Pasadena.

On returning to Tucson, several of these long sequoia records were dated, including one of 2,600 years, but it finally seemed best to postpone the complete study of this material to a time when proper attention could be given to old and prehistoric records in connection with climates of the past. Hence, its further discussion will be reserved for another time.

COAST REDWOOD RECORDS

The value of very long and old ring records is so obvious that every effort has been made to discover them. The coast redwood is a very available tree, growing to a great age, but its preference for the coast's even climate and its avoidance of winter snows led many years ago to doubts of its usefulness in these ring and climate studies. Moreover, about 1912 the late Julius Kapteyn did some counting on the rings of the coast redwood in the hope of finding climatic or solar correlations, but was disappointed. At any rate, the possibility of its usefulness deserved a real test and two groups of this species have been collected.

SANTA CRUZ GROUP, 1921

A trip made on February 20, 1921, was arranged through the kind assistance of Mr. R. E. Burton, of the high school in Santa Cruz, who took me out some 15 miles in a northerly direction from that city to a point near Major's Creek, where redwood trees had recently been cut. This location was in the upper part of the low range of coast hills, but on the eastern slopes, so that the drainage was toward the northeast and inland at that point. The first trees selected were at the upper end of a gully, often dry; others were cut in the valley bottom and others on the very steep slopes of a side-wash. The 7 specimens collected there were studied for months and no satisfactory cross-identification was found. Trees 10 feet apart cross-identified and gave apparently good records, but other trees 50 yards away gave a different record which could not be identified with the first. In the outer parts of some good specimens the rings would interlace in a way never noted in the big sequoia; for example, some red rings merged in one direction with the ring next outside and in the opposite direction with the red ring next inside. Dating was therefore hopeless and has not been accomplished to this day. The general age of these trees was not great, probably from 300 to 700 years.

SCOTIA TRIP, 1925

The above negative result was not conclusive, for it might be a characteristic of the locality chosen or of the southern redwoods only. So the long auto trip of June 1925, described later, was directed to the redwood region of northern California. We motored from Grant's Pass, Oregon, to Crescent City, on the extreme northern coast of California, and thence through those wonderful redwood groves to Eureka and Scotia. At Eureka, the center of the redwood-lumber industry, I consulted representatives of the Forest Service and was referred to Mr. Percy J. Brown, whose mill and forests were on or near the main highway to the south. The general area included a square mile or so of bottom land some 30 feet above the level of the Eel River. This land rises very gently toward the hills on the south, but the slope grows steeper in the outwash-fan from a small canyon entering the hills. Twelve stumps were selected of different sizes and at various scattered points. Of these, three were high up on the ridge forming the east side of the canyon. Here the cutting had been done some years and the young sprouts of redwood from the stumps formed dense and tangled masses which had to be cut away in order to get at the stumps. In the bottom lands below the cutting had been recent, some of the trees having been felled only a few weeks, so there was no difficulty about getting the final dates. The V-cuts were 4 to 6 inches wide and deep and thus were excellent specimens, well selected and in perfect condition. They were prepared and mounted by Mr. Swan Erickson at Tucson under my direction and cross-compared by him and later by me, but no cross-identification was found. Some of the bottom-land specimens seemed to have perfectly clear records, yet with close study the different trees did not agree. It may be that further study will produce some way of using these good specimens, but so far they are not usable in this study of climate and solar activity. This is unfortunate, since many of them carry records over a thousand years in length.

DEFICIENCY OF THE COAST REDWOOD

Though it is true that years ago the theory was entertained that winter snow is important in producing trees that give good climatic records, this failure of the coast redwoods was a surprise. Probably the subsoil water-supply and certain habits of the tree itself increase these nonclimatic variations. The trees get much moisture from the coast fogs, and Mr. W. P. Hoge, of Mount Wilson, tells me that in a fog the trees show some very curious anomalies in their capacity to take moisture from the air. Again, if moisture is in too large a quantity, sunshine would be the controlling factor in growth, though this is not at all likely in the southern groves. But a greater difficulty lies in the way these trees reproduce after fire, which is by sprouts from the base of the mother tree. Hence, these trees when near together are apt to be connected underground. This method of reproduction leads to very erratic growth, as observed by Dr. Emanuel Fritz, of Berkeley. In a letter dated May 15, 1923, he says:

> "This section of second-growth redwood is interesting because it shows a large number of rings merging into one and thus on some radii giving an incorrect indication of the age of the tree. In March we cut three-quarters of an acre of second-growth redwood 65 years old and under, and found to our amazement that trees were older at the top than on the stump. Very careful study soon brought to light the fact that we were not counting the rings on corresponding radii. After this discovery we had no further trouble. As you know, redwood sprouts very freely from the stump. As these suckers mature, they crowd out one another and leave but two or three in a clump. Often

the cambium layer is common around the group. We noted that on that side of the tree which faces closely another sprout, there is a dearth of growth-rings. On that side also there is practically no foliage clear up to the tip. The most peculiar thing about this lack of ring formation on one side is the sudden change from the normal to the abnormal."

In another letter soon after, he says:

"The trees cut in this experiment . . . . were many of them sprouts. Two to six sprouts, 15 to 35 inches in diameter at breast height, were found around many mother stumps. This sprout-clump habit makes the trees touch one another at the base (sometimes after 50 years to develop a common, or rather a continuous cambian ring for two or three trees at stump height) and to be separated at the top by 3 to 6 or more feet. Tree No. 90, from which the specimen was cut, was of this class. The crown was all on one side. The most difficult thing to explain in the specimen seems to me to be the reason for the sudden change from normal growth to asymmetry and then a return to the normal."

The coast redwood may some time be used in the study of climate and solar activity, but its interpretation is so complicated that for the present it can not be included in this study of modern and historic trees.

OLD PINE RECORDS

For climatic records involving rainfall as the most important factor, no tree has yet been found superior to the yellow pine of the arid Southwest. It combines a wide range of growth with excellent sensitiveness and a reluctance to drop rings completely in deficient years (as the junipers do). Next to it, perhaps, comes the Douglas fir, which has larger growth with usually greater sensitiveness, so that for the same size of trunk it has fewer rings with over-exaggerated representation of climatic changes. Therefore, extension of climatic records in the pine trees is most desirable.

SEARCH FOR OLD TREES

In the summer of 1919, Flagstaff was visited primarily for the purpose of investigating certain buried pine trees in the recently filled land immediately north of town, which will be described in another place. September 10 was spent in a "University" section, 5 miles south of town, a section which had long been pointed out as having most beautiful pines with clear trunks, suitable for fine lumber. These trees were on nearly level limestone, breaking to lower levels at their south edge and protected to the west by the volcanic bulk of Woody Mountain. There seems to be no special protection from the occasional powerful northeast wind. This region had been cut over recently and it was easy to select the large stumps with fine grain.

Of the 8 radials cut (Fl–33 to 40), 5 had an age of 500 years. Only 2 such trees had been found before. Thus by one day's work a reliable 500-year record was obtained (see Plate 6).

Burnt centers—All this seemed so encouraging that on August 28, 1922, another visit was made to this locality for the purpose of collecting "burnt centers." It had long been hoped that the tree record could be carried back before 1,400 A. D. by finding stumps or logs of earlier origin which in some way had been preserved. For example, a tree blown down by the wind might be buried and thus preserved, or it might have fire injury which would cause the central parts of the stump to fill with pitch and thus withstand weathering. So on this visit the larger burnt stumps were sought and partial radials cut from their centers. Out of 5 so collected, numbers Fl–95 to 99, one was too complacent for dating, 2 began about 1500 and 2 began before 1400 A. D. Of these two, one undoubtedly started by 1350, but the very center had rotted away and no real gain was made. Yet these two were thoroughly filled with pitch and presented records which match in a remarkable manner certain dated beams from the pueblo buildings of the Hopi Indians.

In the summer of 1920 two other 500-year trees were reported to me at about the same time. On June 17 a radial from Fl–41, a 66-inch stump in the northwest corner of Fort Valley, was cut. This very old tree stood at the edge of the flat valley floor, in good soil, near large outcroppings of volcanic rock, on which the Southwestern Forest Experiment Station stands. Mountains protected it to the west, north, and east, but not especially on the southwest and southeast, and southwest winds are sometimes very strong.

On the following day another stump of even larger size was visited near the top of Woody Mountain, 10 miles to the south. This was numbered Fl–42. By courtesy of Mr. T. A. Riordan, president of the Arizona Lumber and Timber Company, a full section of this splendid tree was cut and shipped to Tucson. Each of these 500-year trees was somewhat complacent; in fact, they and the still older tree mentioned below have decidedly less sensitive records than the previous 7 trees of that age. Five of these 7 had come from the university section, some 3 miles east of Woody Mountain, and 2 collected in 1906 had come from about 2 miles west of the same mountain.

A 640-year pine—In early July 1923, Forest Assistant Merker and Forest Examiner M. Westveld discovered a pine stump in the canyon a mile up-stream (south) from Fisher's Tank and about 5 miles southeast of Flagstaff. By their first count this tree was 640 years of age when cut and subsequent examination confirmed that figure. By courtesy of Mr. G. A. Pearson, director of the Southwestern Forest Experiment Station, a large half section was cut for me and

A. Site of 500-year pines, Flagstaff, Fl. 35, in foreground; looking south

B. Stump of 640-year pine, Fisher's Tank, Flagstaff

sent to Tucson, and later (July 13, 1926) he showed me the stump, of which I include here a photograph (Plate 6, *B*). The canyon is about 200 feet deep in the horizontal limestone strata and extends north and south. Water flows occasionally. The stump is on the east side of the canyon, 25 feet above the bottom and 50 yards from the usually dry wash. The slope of ground about it is about 30°. The date of starting was undoubtedly close to 1275 A. D. The earliest measured ring is 1284, but a serious injury occurred, probably in 1294, greatly reducing the growth for some 8 years. Much decay has occurred at this point, and though the dating is probably correct, the normal values of the ring-width are profoundly reduced. Since the first hundred years in this record were new, three radii were measured and the average taken. The growth is somewhat complacent, but much information is given by it for that century. It is probable that important checks on it will be obtained from early historic beams in the Hopi pueblos. This discovery renewed interest in the search for very old trees, and it is possible that some living trees of similar age have already been found.

Other 500-year pines—A 500-year pine was found in the group of 8 from the Charleston Mountains, near Las Vegas, Nevada. It showed with the other trees there a record rather intermediate between the Arizona and California values. Also a fine v-cut from a pine stump in the Crater National Forest of southern Oregon near Kirkford has been sent me by the kindness of Lumberman John D. Holst, of that locality, acting for Mr. Fred Ames, assistant district forester at the Portland, Oregon, office. In this connection, also, one might mention the extraordinarily old juniper near Logan, Utah, of which a description has come from Supervisor C. B. Arentson, located there.

PREHISTORIC MATERIAL

The search for old pine records has taken a new turn in the use of early historic and prehistoric pine logs in the Hopi villages and the ancient ruins of the Southwest. This really began in 1916, when Mr. Earl H. Morris, for the American Museum in New York, sent me several early historic logs from Gobernador Canyon, near Aztec, New Mexico. This led to a series of specimens from the ancient ruin at Aztec.

Aztec sections—A trip to Aztec was made in August 1919. An examination of the logs in this ruin led to the construction of the tubular borer, which produces cores 1 inch in diameter, giving the series of rings from the outside to the center of the log without impairing its strength and without disturbing the original house construction. Following this visit, Mr. Morris spared no effort in getting me specimens from some 50 logs used in the construction of that wonderful ruin. Nearly all of these cross-identify perfectly in the Aztec-Pueblo

Bonito chronology. It seemed necessary to get some modern trees from that vicinity, so Mr. Morris took me 40 miles north to Basin Mountain, in southwest Colorado, where some 10 different trees were sampled. To these were later added 9 tree sections from a point about 20 miles east of Aztec. These together make a very satisfactory group known in my lists as the "Modern H's," H being the group letter applied to the old Aztec material.

Chaco Canyon beams—The Aztec sections gave a fine ring record more than 200 years in length, but of unknown date. As soon as its real date becomes known, that much length can be added to the climatic record in the southwestern pines. An early shipment of Aztec sections included several from Pueblo Bonito in Chaco Canyon, some 50 miles to the south. These specimens came from the American Museum in New York City, where they had been deposited by the Hyde Expedition 25 years before. Very soon these were found to cross-identify with the Aztec sections, and they began to improve and extend that prehistoric record. Then Mr. Neil M. Judd, director of the National Geographic Society Expedition at Pueblo Bonito, became interested in the possibility of developing the chronology of Pueblo Bonito by the ring records and he has collected and sent me nearly 160 excellent specimens, mostly from that one ruin. Nearly a hundred of these I have been able to place exactly in the Aztec and Pueblo Bonito chronology. This chronology is referred to as R. D. or relative date, since its true location in our numbering of years, "Anno Domini," is unknown. This Pueblo Bonito material has increased the prehistoric ring record so that it extends accurately from R. D. 230 to R. D. 543, a range of 313 years. A single beam extends it with uncertainties about 40 years later. So if this material could be dated, some 350 years of record would be added at one stroke.

In connection with this collection two trips have been made to Chaco Canyon, one in early September 1922, to get a better knowledge of the beams there and of the problems connected with their dating, and the other in September 1926, to study the living pines in that region. On each occasion many specimens were collected, and on the second trip much was seen of special interest in connection with climatic indicators in trees, which will be mentioned in a later chapter.

National Geographic Society beam expedition—It is evident that two different interests join in the attempt to date the beams in the ancient ruins of the Southwest, namely, the extension of climatic and solar records in trees, and the archæological and human interest in the age of those wonderful ruins. For the second reason, the National Geographic Society has encouraged and supported the further collection of early historic and prehistoric material and otherwise assisted in the dating of these prehistoric beams. In general, two distinct dating methods are in view. The first is the "bridge" method, by which we start with old living trees and cross-date the early parts of these with late parts of earlier trees, and so on till a real ring record is built back to the age when the ruins were under construction. The other method is the "sequoia comparison" method by cross-dating with the sequoias, whose great age without doubt covers the period of building of these ruins. The best result would be one derived from a complete agreement of these two methods. Perhaps the stronger of the two methods is the first or bridge method, but it promises to require large collections from many different ruins, beginning with the early historic and going back to the period desired. Consequently, in June 1923 an expedition set out for the purpose of making such collections under the charge of Dr. J. A. Jeançon of Denver, assisted by Mr. O. M. Ricketson, of the Carnegie Institution. I went with them for the first 10 days in their visits to the Hopi Indian villages, where some 22 specimens were collected. They then continued the trip, covering generally the southwestern area, including such places as Canyon de Chelly, Chaco Canyon, Mesa Verde, and the Rio Grande Valley. To the present time their collections have not been finally and thoroughly examined (such work will be done in connection with the study of past climates), but it is practically certain that extensive gaps remain in the long interval from the Aztec and Pueblo Bonito chronology to A. D. 1300 or 1400, when the living trees began their record. Nevertheless, this bridge method is probably only delayed, for the collection from Pueblo Bonito reveals the possibility that in some Hopi Pueblo or late prehistoric ruin will be found beams cut in ages different enough to cover the long interval desired.*

CALIFORNIA AND ARIZONA CROSS-DATING

In the presence of the gaps above referred to, the sequoia comparison method becomes of increased importance and has played an important part in directing our effort in the last few years. The visit to the Calaveras Grove in 1924 and to the Springville Grove in 1925 were primarily to aid in this problem. The problem itself was stated above in describing the purpose of the fourth sequoia trip, page 52.

CHARLESTON MOUNTAIN TRIP

In connection with the dating problem between Arizona and California, the Charleston Mountains, at the southern extremity of Nevada and about midway between the Flagstaff area and the best sequoia region, were visited and collections made. Senator E. W. Griffith, of Las Vegas, Nevada, kindly took me out on July 9, 1924, by automobile some 30 miles west to the summer resort at about 7,500 feet elevation in these mountains. The resort is located in a large, deep canyon on the east side of the mountain and well up in the pines. A delightful brook runs much of the time. The ring record from the trees collected here is actually intermediate between Arizona and California, agreeing in some parts conspicuously with the Arizona trees and in other parts with California. The full discussion of these characteristics, in order to see whether they help to solve the cross-dating problem, is planned in connection with the study of past climates.

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*At the time of reviewing this chapter a group of 25 beams from "Wupatki" near Flagstaff has shown that this ruin was built some 30 years later than Aztec. It seems very probable that in time the "bridge" method will be successful.

VII. TREE RECORDS: GEOGRAPHICAL DISTRIBUTION

The understanding of any special distribution of ring characters over great areas is increased by personal acquaintance with the region. So, in addition to much travel in the Southwest, both within and without the State of Arizona, the writer has made two special trips in the study of geographical distribution of tree-growth.

WESTERN CIRCUIT, 1925

This trip was made easterly from Tucson to the Rio Grande Valley, thence up-stream to Albuquerque and east again to Santa Fe, where the SF group had been collected in 1922; thence through the pine-covered mountains to Las Vegas. Halfway between these cities we passed Pecos, where the "L" group of four trees had been obtained, by aid of the Forest Ranger. However, only one of these proved suitable for dating, and so this is not retained as a group. The next day carried us over the wide elevated plains of northeastern New Mexico to Raton, whose mountain pass through the Rockies is high enough to be pine-covered. Three of the trees near the road were bored, but only one could be dated reliably, and as we already had a group from Cloudcroft, New Mexico (CC group), this single tree is omitted. Later we went along the eastern base of the mountains to Fort Collins, Colorado, and Laramie, Wyoming. In the low hills between these two places, the group LW (Laramie, Wyoming) was collected near the road.

The eastern face of the Rocky Mountains, extending north and south for many hundreds of miles, is a striking feature of western contours, and the groups in New Mexico, Colorado, and Wyoming along this line and partly also the small Yellowstone group from Specimen Ridge in the northeast corner of the park (collected in 1920) give certain interesting characters which will be referred to later.

The next stop for collecting was 60 miles northwest of Baker, Oregon. At a point where pine trees border the road as it passes over the Blue Mountains, the BO (Baker, Oregon) group of 8 was collected. On the eastern slopes of the hills near the road at The Dalles are more yellow pines, of which a small collection was made, known here as the DL (Dalles) group. In the low coast hills 25 miles northwest of Portland, a large group of Douglas firs was collected in 1912, as described in Volume I. It now appears that this group, called OC (Oregon Coast), does not cross-identify with the other western groups, probably because its location close to the coast gives a very different climatic environment.

The primeval forests of the State of Washington were extensively cut along the settlement-line marked by the highway between Portland and Seattle. Much of the land was burnt over and the huge burnt stump is a common sight. Stumps were examined in different places and ring samples were collected at Victoria, British Columbia, at Blyn, Washington, and at Toledo, on the Oregon coast, but the growth was so exceedingly complacent that no special effort was made to form a group. However, there is no real doubt that group characters will show, if the right tree and location are found.

WESTERN CONTOURS AND RAINFALL

The important mountain ranges of the western States extend in north-and-south rows, whose western slopes precipitate moisture from the westerly winds. The long valley running north from the Gulf of California, with the smaller parallel San Joaquin Valley in central California, is the driest area, because the westerly winds are drying winds as they descend into them.

Mechanism of Arizona summer rains—The maximum rainfall on the coast is in winter, but the maximum in the northern parts of the dry valleys just mentioned is in late spring, when their warming causes the air to rise and move to the east and "pull" in the westerlies. In midsummer it is so hot that the moisture is reabsorbed even before it falls and the amount that reaches the ground is small. The same summer "pull" draws moisture-laden air from above the Gulf of California far to the south (whose water temperature at Port Libertad in September 1923 was 87° F.), and perhaps from other warm bodies of water. This air, as it is drawn up over the mountains and plateaus in its northward-moving path, gives up its moisture in the common torrential summer rains of that region, strongest near the Gulf and fading out in Utah.

Prediction possibility—If this statement of the possible mechanism of our summer rains is correct, it would seem possible to predict their amount, some months at least beforehand, by some formula involving chiefly the mean temperature of the water in the Gulf of California and of the desert areas of the western valleys.

The Rocky Mountains—The Rockies are high enough to catch the westerlies and intercept a remnant of their moisture, and thus they partake year by year to some degree in the winter variations which come to the Pacific Coast. But in the warmer months the mechanism just referred to as acting north from the Gulf of California produces a similar effect north from the Gulf of Mexico, and the eastern Rockies show a great summer maximum.

THE THREE ZONES

Thus, in reference to climatic types, there are three zones lying in north-and-south strips delineated by the mountain ranges. On the west is the Pacific or Coast zone, where the precipitation is only in winter, from the westerly winds coming in off the ocean. The arid interior region forms the Arizona zone, whose higher points where the pines grow intercept the westerlies and partake strongly in the variations of the coast. This zone has a secondary rainy season in midsummer, torrential in character and producing for the most part only slight effect on the tree-growth. To the east is the Rocky Mountain zone, which catches a remnant of the coastal variations and gets its chief moisture supply in summer.

Latitude effect—In each of these zones there is a strong latitude effect. On the coast the westerlies are very powerful in the higher latitudes, weakening south of San Francisco and becoming gentle at San Diego. They disappear entirely in the tropics. In the valleys of the central zone the spring rainfall maximum of the north changes to the well-defined winter and summer rainy seasons of Arizona. The eastern or Rocky Mountain zone has less latitude change than the others. The total rainfall increases as we go south by the increasing amount of summer rains. In Texas, and still more in Mexico, it begins to show a temporary diminished rainfall in July and August at the very peak of the maximum. Perhaps this is actually the tropical winter minimum of the southern hemisphere reaching over thus far into northern latitudes.

THE PUEBLO AREA

The Pueblo area trip was made in behalf of the National Geographic Society in connection with studies of the Pueblo Bonito chronology. It seemed advisable to visit and test the pine and spruce regions from which the prehistoric Indians drew their timbers and find out whether such regions agree with the Flagstaff areas in their tree-growth.

The Hopi villages—These villages, still occupied, lie along the southern edge of a raised and sloping plateau called the "Black Mesa," whose surface is dissected by canyons and whose highest point, some 75 miles north of the villages, is near Kayenta.

Kayenta—The 24-hour trip from Flagstaff to Kayenta was made on September 4 and 5, 1926. The settlement is in a valley just east of Mount Lolomai, the highest point of Black Mesa. Mr. John Wetherill, for many years well known in this region, took us to the mountain top, 4 miles in a car, 4 or 5 more on horseback, and then a climb of 700 feet on foot. Samples collected in several different places all show the Flagstaff ring record, as do the rings in the beams of the Wetherill house.

On September 7 we started to Chin-lee, 72 miles southeast, passing Chilchinbeto at 16 miles and confirming the agreement between Black Mesa and Flagstaff by some specimens there.* At Chin-lee we cut radials from logs in the store of Mr. L. H. McSparron, who very kindly gave the necessary permission. These logs came from the Lukaichukai Mountains east of the Chin-lee Valley, south of the Chuskas and north of Fort Defiance and Gallup. A day on horseback was spent in the wonderful canyons there, De Chelly and Del Muerto. Then we drove southeasterly up onto the Lukaichukai Mountains and obtained borings in several places, ending at the sawmill 13 miles north of Fort Defiance. These borings and the radials from Chin-lee agree with the Flagstaff series.

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*Later, on the return trip, we stopped at Oraibi, the westernmost of the Hopi villages, and cut radials from logs of spruce from Piñon, 30 miles northeast, with the same result.

We motored southeast to Gallup and then 100 miles northeast to Chaco Canyon, and there a most interesting search was made for living pines, a number being found at distances of 2 to 20 miles east of Pueblo Bonito. These pines, which appear to be a remnant of a great forest on those mesas in past ages, also show the Flagstaff series of rings. From Chaco our return trip carried us to Gallup, Holbrook, and the Petrified Forest, Keam's Canyon, Walpi, Oraibi, Leupp, and Flagstaff, 16 days from leaving it.

Rio Grande Valley—During a trip to the Rio Grande Valley in April 1927, specimens of tree-growth from the Zuni Forest, south of Grant's, New Mexico, and from the Jemez Mountains, west of Santa Fe, were obtained. Each locality shows a perfectly clear Flagstaff record.

Navajo Mountain—By courtesy of Mr. H. Richardson, a trip was made in May 1927 to Navajo Mountain, Rainbow Bridge, and Rainbow Lodge. Specimens of Douglas fir from the south slopes of the mountain show a perfect Flagstaff record. These recent collections therefore leave no further doubt that the whole Pueblo area west of the Rio Grande is homogeneous in its tree-growth and forms part of the large Flagstaff area.

SOUTHWESTERN CONTOURS

The large southwestern arid area is bounded on the west by the range of Southern California mountains, including San Antonio, 10,080 feet, San Bernardino, 11,600 feet, and San Jacinto, 11,000 feet, which, therefore, form a great rampart impeding the westerly winds. East of this range is the Imperial Valley, with the Salton Sea some 200 feet below sea-level. The Charleston Mountains form an isolated island at the southern point of Nevada. East of the Colorado River the land rises to the plateau of northern Arizona, while in the southern part of Arizona the land rises to the east very gradually, with many "island" mountains high enough to have pine trees upon them. The Mogollon Mesa, often called the Rim, is the bold and lofty southern edge of the Colorado plateau. It cuts across the central part of the State, pointing generally a little south of east. South of it are the island mountains; north of it the land descends gently to the Little Colorado River and then rises gently to the States on the north. On this slope the great Black Mesa has large cedar forests, with pines in the canyons and along the northern edges. Then to the east is the Chin-lee Valley, and east of that, on the border between Arizona and New Mexico, is the range called Chuskas on many maps, with a southern part called the Lukaichukais. These carry extensive pine forests. The next pine-covered range is a hundred miles east and forms the western boundary of the Rio Grande Valley. This range has Mount Taylor at its southern end and the Jemez Mountains west of Santa Fe. Chaco Canyon is in the large area between the Chuskas and the Jemez Mountains. It is surrounded by mesas which probably once held pine forests, but the mountains just named are higher and its rainfall is small. East of the Rio Grande Valley the big masses of the Rocky Mountains begin.

WESTERN PINE GROUPS

Statistics—The whole number of tree records minutely examined up to date is about 1,100, and the total number of rings is close to 210,000. Of these, about 175,000 have been dated and measured. The extensive failures to date the coast redwoods are largely responsible for this difference between rings examined and rings measured, and many of the groups have had a small proportion of the trees which could not be dated. The number of trees included in the 42 groups whose cycles are studied below is 305 and the number of rings dated and measured is 52,400. These trees are practically all western yellow pines, with a few Douglas firs here and there.

Zone statistics—The 42 groups are divided into three zones: (1) the interior or Arizona zone, where this study began and has had the greatest extension; there are 14 groups in this zone, with 104 trees and 21,210 measures; (2) the eastern or Rocky Mountain zone has 15 groups of 82 trees and 14,135 measures; and (3) the western or coast zone has 119 trees in 13 groups, with 17,055 measures.

Miscellaneous groups—A number of other groups not included in the subsequent discussion of cycles follow the western pine groups. They consist of groups of different kinds of trees, groups of good trees which did not have enough material, such as the Raton and Pecos groups of yellow pines with only one record each, of trees which could not be dated, such as the coast redwood, and of groups from distant localities.

Group treatment—In the 42 western cycle groups only the individuals are used which can be dated and also only those parts of each individual which can be dated with certainty. In nearly every group the curve of each individual tree has been standardized as described in a previous chapter. Thus the different trees in a group have equal weight and the age effect in the trees is largely removed.

Analysis—Three analyses were made, namely: (1) the full length of the group curve, using maxima; (2) the part of the group curve subsequent to 1750 A. D., using maxima; (3) the part of the group curve subsequent to 1750 A. D., using minima, that is, plotting an inverted curve and then cutting out and analyzing the higher (negative) ordinates as usual.

Precautions—Knowing the possibility of prejudice and systematic error in analyzing this large number of curves, several precautions were observed: (1) Settings of the White cyclograph were made without knowing what the reading was going to be; (2) full analysis of each curve was made without knowing which curve it was; (3) each of the three analyses was carried through the complete list of curves in one continuous sitting of four or five hours, so that possible errors of adjustment or of judgment would apply equally to all groups; (4) the instrument was calibrated from time to time with standard curves, and its errors were of the order of one-tenth of a unit of period, which is less than the error of an average setting, which is one to three tenths of a unit, depending on conditions. Four critical parts of the reduction process were invariably done by the writer, namely, dating the rings, drawing the standardizing line, marking the cutting line for the cycle plot, and making the cycle analysis. Other parts were done mostly by assistants, such as mounting, measuring (checked afterwards by the writer in most cases), tabulation, plotting, smoothing, and tracing and cutting the cycle plot.

Analysis report—A cycle is reported below only when it occurs in two of the three analyses, and its relative excellence is shown by a number in parentheses following the cycle-length. This number may be considered a "weight" and so an approximate amplitude. Unit weight, meaning medium or average conspicuousness of the cycle, is omitted. Weight 2 means a fine cycle and weight 3 a remarkable cycle as viewed in the cyclograph. Cycles occasionally show a lesser secondary maximum and very rarely two secondary maxima. In such cases the fraction $\frac{1}{2}$ or $\frac{1}{3}$ respectively, in the parentheses with the weight, gives indication of this doubling or tripling.

Abbreviations—For convenience, the names of the groups are sometimes reduced to an abbreviated form which consists of some initial letters as suggestive as possible. These letters are given after the group title.

ARIZONA REGION

FIRST FLAGSTAFF GROUP (FL)

This group was collected in 1906, 1 or 2 miles west of Woody Mountain and some 10 miles southwest of Flagstaff. Nineteen trees numbered 7 to 25, were used; Nos. 1 to 6 were not preserved and therefore were not corrected by cross-identification, which was applied to the others in 1912. The 19 original sections have been retained and two sets of radials have been cut from them; one is the set measured in 1906 and cut in 1912 and the other was cut about 1925, so that accidental loss of the fragmentary pieces of the original sections would do no harm. The curve values as extended to 1910 are given in the appendix of Volume I, to which volume reference is also made for the curve itself (p. 25) and further details. Measures were by ruler. There were so many in this group that for the present purpose it did not seem necessary to standardize each tree-curve, as has been done in nearly all of the western-pine groups. The smoothed curve shown in figure 4 was made by a graphic Hann. The cycles are 6.9 (3), 13.6 (3), 20.6 (2), and 28.3 ($\frac{1}{2}$).* It still remains uncertain whether the cycle 20.6 years is a real value or whether it is a combination of two, of which one is under 20 years and the other about 21 years.

FLAGSTAFF 500-YEAR GROUP (FLU)

This group was collected September 10, 1919. Mr. J. F. Freeman measured the specimens by the cathetometer method. Long records were sought at that time and the two 500-year trees, Nos. 12 and 13 in the previous Flagstaff series, were completely remeasured and added to the five similar trees in this group, Nos. 33,† 34, 35, 37, and 40, and a table of seven (unstandardized) trees produced. It is a plot of their averages, 1750 to 1917, of which a graphic Hann is shown herewith in figure 4. The use of the same two trees in each of these Flagstaff groups probably has no real effect on the similarity between the two groups, which is very marked, for all these trees give very nearly the same record. The cycles found in this group are 14.0 (2), 20.6 (3), 26.7 ($\frac{1}{2}$), 29.1 ($\frac{1}{2}$), and 40 ($\frac{1}{2}$). The 20.6 varies from 20.2 to 21.0. The two near 28 are perhaps variants of one cycle.

FORT VALLEY GROUP (FV)

This group is made up of complete sections cut in Fort Valley, 12 miles northwest of Flagstaff, by Mr. G. A. Pearson, for the purpose of studying group effects, or the effect on tree-rings of near neighbors. But practically no effect was found unless the neighbor was within 5 or 10 feet. The trees grew one-quarter mile northeast of the experiment station, elevation 7,300 feet. Mr. L. R. Patterson measured these rings by the auto-plot method. Each tree was standardized. The final table and plot were made by Mr. W. G. Austin and the cycle plots by Mr. F. M. Douglass. The curve 1686 to 1920, shown from 1750 in figure 4, resembles FL and FLU and is equally typical of the

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*It will be noted that this fraction means doubling and not weight.

†Nos. 26 to 32 were cut east of Lake Mary in 1911 and are often called the LM group. They are given in the curve on page 27 of Volume I, and as they were only small pieces cut from the edge of the stumps, they are not used in this study of western cycles.

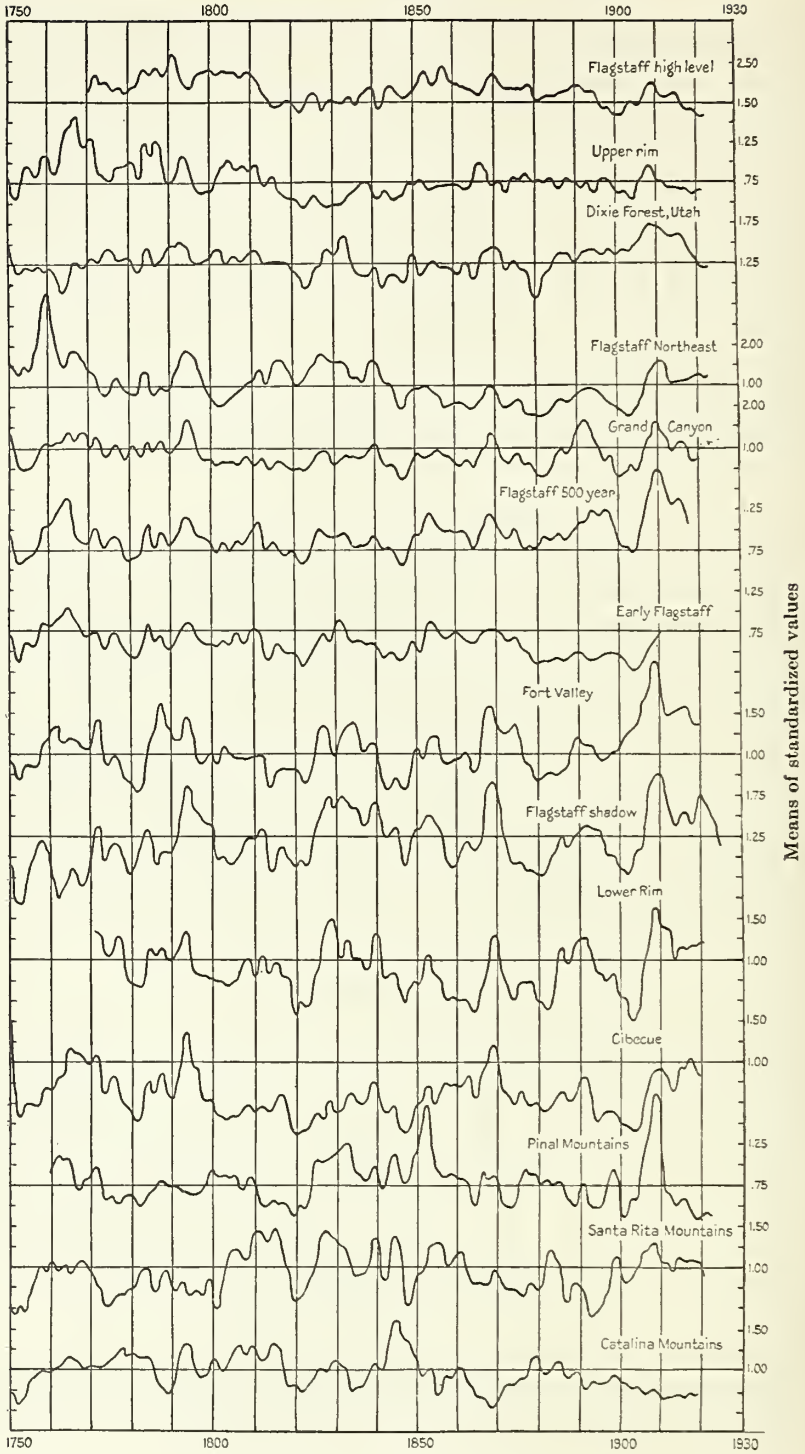

FIG. 4—Arizona zone, smoothed group curves

central Arizona area. It shows cycles as follows: 13.1, 14.5, 18.5, 20.5 (3), and 35 (3, $\frac{1}{2}$). The 13.1 and 14.5 are very possibly variants of one about 14 years. The 20.5 again varies from 20.0 to 21.0.

HIGH LEVEL GROUP (FLH)

The idea of testing the effect of altitude on the ring-growth was held from an early date. The first actual collection for it was done on June 19, 1920, when Dr. E. J. Brown and the writer went on foot up the canyon above Shultz Pass, where the Weatherford Boulevard has recently been constructed. But the specimens were crudely cut and it was felt that it would be preferable to test tree-growth on the west or southwest slope of the mountain. Accordingly, on July 11, 1920, a trip was made up the southwestern ridge of the mountain from the southern end of Hart Prairie to the cabin used by the experiment station at an elevation of 10,500 feet. Director Pearson and Mr. Haasis of the staff were of the greatest assistance. A very interesting group, numbered Fl 69 to 80, was obtained, including Douglas fir, cork-bark fir, limber pine, fox-tail pine, and Engelmann spruce. But this seemed to combine too many different species over too great a range of altitude; accordingly, the group of yellow pine increment-cores here used was collected with the aid of Mr. Pearson on July 12, 1924, at elevations averaging a little under 9,000 feet, that is, really in two subgroups, one at the south end of Hart Prairie and the other at a little over 9,000 feet altitude.

These 10 cores were measured by Mr. D. A. Hawkins, using the long-plot (longitudinal plot) method, and were then tabulated and averaged and the curve, 1770 to 1923, plotted without standardizing. A graphic Hann, shown in figure 4, was made by Mr. F. M. Douglass. In general appearance this smoothed curve has all its variations greatly diminished and is otherwise somewhat discordant compared to the usual Flagstaff tree-records. It introduces a 17-year cycle, which is not common in this region; but its cycles belong to the Arizona class and are as follows: 6.9 (2), 9.1 (oc. $\frac{1}{2}$), 13.7 (2, $\frac{1}{2}$), 17.3 (3), 20.5 (2, oc. $\frac{1}{3}$), 27 (oc. $\frac{1}{4}$), and 35 (2, oc. $\frac{1}{2}$).

FLAGSTAFF SHADOW GROUP (SH)

The old-time winter road to all points north of Flagstaff passed east of the San Francisco Mountains because it was drier, warmer, and had less snow than the west side. The forest regions east and northeast of the peaks are shaded by the mountains from the wet westerly winds, and the special effect observed in this group and others is called the shadow effect. This group of five Swedish increment-cores was collected on July 13, 1924, in a specially selected area nearly on a line between Sunset Crater and the peaks, and about half a mile west of the main highway. At this place the elevation is very little above that of Flagstaff and is about the same as that of the Fort Valley group, with which the curve, therefore, can be compared for the shadow effect. Mr. Hawkins measured these specimens by the long-plot method and, without standardizing, plotted a curve from the averages. This curve, 1717 to 1923, was Hanned mathematically and the cycle plot was made by him also. This smoothed curve from 1750 on is shown in figure 4. The great variation between maxima and minima is at once apparent and is characteristic of lower and drier altitudes. The shadow effect does not appear to differ much from simple reduction in rainfall, equaling in this case the effect of about 1,500 feet change of altitude. The spacing of the maxima is strongly of the Flagstaff or Arizona type. The observed cycles are 14.1 (3), 19.4 (2), 27.3 (2, ½) and 40 (2, oc. ½).

FLAGSTAFF NORTHEAST GROUP (NE)

This group was collected on June 14, 1923, in connection with prehistoric dating problems, to determine with certainty whether the part of the Flagstaff forest area nearest the prehistoric ruins carries the same ring records as the very old trees just south of town. Dr. E. S. Miller, of Flagstaff, was kind enough to take me out 19 miles on the Tuba road and there, at the edge of the forest, I took four increment-borings. Mr. Hawkins measured these in 1923 by the auto-plot method. These were thoroughly rechecked by the writer (as in all cases). These individuals were so nearly alike in average growth that they needed no further standardizing. The curve, 1678 to 1922, identifies exactly with the Flagstaff record. It was smoothed by graphic Hann by Mr. Austin and the part from 1750 on is shown in figure 4. The cycle plot analyzes as follows: 8.5, 11.6 (2), 14.3 (2, oc. ½), 19.4 (2), 27.7 and 36 (2); these classify as Arizona type, though the 11.6 is not so common as on the coast.

GRAND CANYON GROUP (GC)

The edge of the Grand Canyon is 65 miles north and a little west of Flagstaff. Leaving the San Francisco Peaks and traveling north, one descends gradually for a time away from the pines, down through the cedars, across a barren area, then up gradually through the cedars and into the pines which border the canyon. Much of the forest area near the canyon is perfectly flat. The Grand Canyon group was taken in early July 1920, at points scattered several miles along the south rim from a little west of Grand View to the Buggeln property, which used to be Tolfree's Hotel, at the top of the old historic Hance Trail, a distance of 5 or 6 miles. The soil here is a thin layer of earth over limestone. There appears to be very little surface drainage and it is probable that the water soaks down through the limestone formation and emerges in springs in the canyon. In the early days, Tolfree's got its drinking-water from artificial "tanks" or pools of standing water formed from the melting winter snow. Mr. Patterson measured 7 of this group of eight **v**-cuts by the auto-plot method in 1922. Each tree record was later standardized, tabulated, and plotted by Mr. Austin in a curve from 1716 to 1919. This curve is of perfect Flagstaff type. The graphic Hann shown in figure 4 was made by Mr. F. M. Douglass in 1926. The cycles belong to the Arizona classification, as follows: 11.7, 14.5, 18.4, 20.8 (2), 23, and 36 (oc. ½).

DIXIE FOREST (UTAH) GROUP (DF)

This is a group of Swedish increment-cores collected and sent me by Mr. William M. Mace, supervisor of the Dixie National Forest, from the Pine Valley Mountains, in the southwestern corner of Utah. As in the case of the Charleston Peak of southern Nevada, it seemed desirable to find some groups intermediate in position between the Flagstaff area and the region of the big trees of California. Mr. Mace writes that these specimens came from the westerly side of the mountains at an elevation of 8,500 feet. This would seem to correspond in topography to group FLH, but their record, though very complacent like FLH, resembles FL more than FLH does. The cores were received October 1, 1923. Mr. Austin measured them by the long-plot method in 1926. Each tree was standardized and the table and averages and plot were also made by Mr. Austin. The curve extends from 1616 to 1922 and shows good resemblance to the Flagstaff curve. It was smoothed by graphic Hann and is thus shown from 1750 in figure 4. Its cycles are of the Arizona type, as follows: 19.6 (3), 27.1, and 40 (2, oc. ½).

UPPER RIM GROUP (RH)

Next to the Grand Canyon, Arizona's most remarkable scenic feature, on a large scale, is the Rim. This is the abrupt southern edge of the great Colorado Plateau. It is an ancient fault-line; the rocks to the north average 7,000 feet above sea-level and 1,000 to 2,000 feet higher than those to the south, with other steep slopes below, so that from the Rim one looks over enormous stretches of Southern Arizona with its island mountains showing faintly in the blue haze of distance. The edge of the Rim stretches across half of the State in a generally uniform direction, but is wavy or zigzag in detail. So, when seen from below, for example, from near Pine or the Natural Bridge, its sinuous length extending easterly as far as the eye can see, could be classed as one of the wonders of the world.

An extraordinarily large and pure pine forest covers this Rim and the adjoining slopes, connecting on the north with the Flagstaff area and extending on the east past the White Mountains and into New Mexico.*

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*Years ago, by kindness of Mr. F. S. Breen, then supervisor of the recently created national forest, it was my privilege to traverse this Rim from Camp Verde to Nutrioso, close to the New Mexican border, in a buckboard. I have no doubt that 600-mile trip from Flagstaff, lasting 26 days, helped to originate this investigation of the history recorded in tree-rings.

Thus the bold, pine-covered headlands of rock overlooking southern Arizona differ in topography from the Flagstaff region, and it seemed worth while to get a group of borings in such a locality. This was easily done in a motor trip from Tucson to Flagstaff, on which I was assisted by Mr. T. J. Randolph. The borings were made on August 26, 1922, two of them at 6,000 feet elevation, near the fork in the highway between Pine and Strawberry, where the road to Flagstaff starts up the big grade. These were numbered 91 and 92 in the Flagstaff series and form the group RL. Two other borings were made at the top of the Rim, where the elevation is 7,000 feet. These were numbered 93 and 94 and constitute the present group RH. It was intended to include all of these four in one group, but the two locations proved so different in their effect on ring-type that it was thought best to separate the pairs. The individuals of each pair agree finely. Mr. Hawkins measured these four cores by auto-plot method. They were then completely rechecked by the writer and individually standardized. The tables and curves were done by Mr. Austin. The curve of the Upper Rim group, 1697 to 1921, smoothed by graphic Hann, and shown in part in figure 4, is very complacent, and has only moderate similarity to the typical Flagstaff curve. Its cycles, however, keep it in the Arizona zone, for they are as follows: 14.7, 19.9 (3), and 37 (2).

LOWER RIM GROUP (RL)

This group, as described in connection with the preceding, consists of two increment-cores collected August 26, 1922, near the fork in the road at the foot of the long Strawberry grade. The elevation is 6,000 feet. Its location is a south exposure with the great thousand-foot wall of the Rim immediately to the north and a low, flat-topped mesa "island" close to the south, standing up a few hundred feet. The curve, 1770 to 1921, smoothed by a graphic Hann, is shown in figure 4. Its striking variations resemble a shadow effect like that in the SH group, which it minutely resembles. In fact, the remarkable likeness between this curve and those of FLU, FV, SH, NE, GC, and J groups puts this collection of groups in a distinctive homogeneous class whose locus extends at least from the Grand Canyon to the Rim, a distance of about 150 miles. The RL cycles are 10.1, 12, 20.1 (3), 23.7, 27.6, and 38 (2, oc. $\frac{1}{2}$). The absence of 14 years makes it resemble the cycle of the Rocky Mountain zone, but as 14.4 did appear in good form in one of the three analyses, its place in the Arizona zone is justified.

CIBECUE GROUP (J)

The Cibecue group of five increment-borings was collected on July 23 and 24, 1920. The area included in this group extends from the store on Grasshopper Creek (15 miles west of Cibecue Creek store) to the small creek about a mile east. This is some 20 miles south of the Rim and about halfway between Pine and Fort Apache. The elevation is under 6,000 feet. The region is reached by motor from the White River Indian School near Fort Apache. The cores were measured by Mr. Patterson, using the auto-plot method, and fully rechecked. The curve, 1652 to 1919, was plotted directly from the averages and cross-identifies closely with the Flagstaff record. The graphic Hann from 1750 on is shown in figure 4. It resembles RL strongly. The cycles are 8.2, 9.6, 12.1, 18.5, 23.8 (3), and 30.5. There was no sign of a 14-year cycle, and therein it resembles the Rocky Mountain curves.

PINAL MOUNTAIN GROUP (PNL)

Surrounded by the lower levels of southern Arizona, the Pinal Mountains form an island 90 miles from the Rim groups described above. To reach them from that part of the Rim, one motors down Tonto Creek and after leaving Four Peaks on the right, passes Roosevelt Lake and Dam. Twenty-five miles beyond are the cities of Globe and Miami, south and west of which are the Pinal Mountains. A road goes to Tucson over each flank. To the east is the Winkelman road ascending almost to the pine level; to the west is the Globe-Superior Highway, a splendid bit of road engineering over a rocky and picturesque table-land. Four borings were made September 5, 1924, above the camp-grounds, southwest of the main peak. These cores were measured by Mr. Swan Erickson, using the long-plot method. Each tree of the three usable ones was standardized and the resulting curve (see fig. 4) shows distinct resemblance to the Flagstaff curve—more in fact than do the curves of the other island mountains. The cycles are 7.6 (2), 10.1, 14 (oc. $\frac{1}{2}$), 23, and 27. This grouping of cycles is classed as general, since it is rather deficient in the special characteristics of each zone.

CATALINA MOUNTAIN GROUP (SC)

The Catalinas are about 60 miles a little west of south from the Pinals. They are a large, rambling mountain mass without distinctive top and form an emphatic northern boundary to the Tucson Valley. The main summit, Mount Lemmon, elevation 9,150 feet, has an inconspicuous rounded top with a fire lookout. Close on its southeast edge is the resort, Summerhaven, with an easterly ridge extending 4 or 5 miles to Bigelow Peak and beyond. Central on this ridge is the beautiful little valley known as Bear Wallow, with the ranger station and Soldiers' Camp. The SC group consists of eight increment-cores and one 350-year V-cut, all usable except one core. Their location extends from Summerhaven to Mount Bigelow. Some are on the very crest of the ridge and some are a hundred feet or so lower down on the south side. The average elevation is about 7,500 feet. The contours are given in some detail, because this group, while internally very satisfactory, is as a whole the most discordant in the entire Arizona area, both in cross-identification of rings and in comparison between smoothed curves. The SC specimens were measured part by autoplot and part by long-plot method. Individual trees were standardized. The final curve, 1567 to 1919, shows a very limited resemblance to curves in the Flagstaff area. After being smoothed by graphic Hann, it shows many reversals of Flagstaff growth, for example, the years near 1630, 1670, 1730, 1847, and 1880 have big growth instead of small. The part since 1750 is given in figure 4. The cycles are 7.5, 9.2 (oc. $\frac{1}{2}$), 11.3, 17.4 (2), 22.9, and 34.7 (3, oc. $\frac{1}{2}$). The presence of 11.3 and 17.4 gives it a resemblance to the Rocky Mountain zone which incidentally has a number of reversals compared to Arizona.

SANTA RITA GROUP (SR)

The Santa Ritas, 9,400 feet in elevation, are 50 miles due south of the Catalinas and form a massive mountain boundary on the east side of the Santa Cruz Valley south of Tucson. The mountain slopes are steep and the summit itself forms an upstanding monument of rock 500 feet high, very striking in appearance. The pines cover the upper parts of the mountain, but favor the north-facing canyons where the snow lingers. Some Mexican species of pine are found here, but they closely resemble the western yellow pine. A group of 10 borings was collected in the upper parts of White House Canyon, the summer-resort region, on May 2, 1921, but these could not be dated, as the doubling of rings by the pronounced summer rains made the annual character very uncertain, a summer condition much more pronounced here than in northern Arizona. So a second group of 6 borings was made December 22, 1921, at higher levels, that is, from 7,500 to 8,700 feet, of which all but one were usable. In this collection I was assisted by Mr. M. S. Lankford. In a recent review it was noted that the Santa Rita tree-records have the intensely small Flagstaff years, 1847, 1902, 1904, and so forth, but are erratic within the group, omissions and change of size making cross-identification very laborious.

Each of the five trees was standardized and the resulting average curve, 1670 to 1921, smoothed by a graphic Hann, as shown from 1750 in figure 4. It resembles both the Flagstaff and the Catalina records. Its minute details confirm the dating of the Catalina specimens, which were at first held in considerable doubt. The cycles are 7.5, 11.2, 14.4 (3, oc. $\frac{1}{2}$), 23.0 (3), and 27.4 (oc. $\frac{1}{2}$). This is distinctly of the Coast type. On the whole, it will not be surprising if these southern island mountains are influenced by some climatic situation distinctly different from the northern Arizona plateau area.

THE ROCKY MOUNTAIN ZONE

YELLOWSTONE GROUP (Y)

This group of five increment-cores of white-barked pine (*Pinus albicaulis*) was collected on August 20, 1920, at the eastern edge of the flat top of Specimen Ridge, west of and opposite the buffalo farm, in northeast Yellowstone Park. The trip was made from Camp Roosevelt with the assistance of Mr. A. G. Whitney. The specimens were cross-identified and dated in 1926. They were measured by Mr. Austin, using the long-plot method. They were standardized and give a record from 1693 to 1919. The curve from 1750, smoothed as usual, and shown herewith in figure 5, does not closely resemble the other Rocky Mountains curves, though its cycles are distinctly of that type. They are 8.5 (3), 10.4, 12.5, 17.1 (3, oc. $\frac{1}{2}$), 25.6, 30.3 (oc. $\frac{1}{2}$). Here we see the 17-year period which is characteristic of this eastern zone.

LARAMIE, WYOMING, GROUP (LW)

This group of four cores, of which three only could be dated, was collected on June 11, 1925, while motoring from Fort Collins, Colorado, to Laramie, Wyoming. At some point not far from the State border the road passes through a slight ravine with pine trees on the steep slopes. The three cores afterwards used were obtained here. A few miles farther on, a very large pine growing in a bleak flat area was bored, but the outer rings were too small for certain dating. These specimens were measured by Mr. Austin, using the long-plot method. The records were each standardized and the curve, 1754 to 1924, was smoothed by graphic Hann, which is shown in figure 5. Though its variations are immense, it closely resembles the typical Pike's Peak curve. Its cycles present the characteristic 17-year period with what are probably some of its variants. The cycles are: 6.3 (2), 8.2 (3), 11.5 (oc. $\frac{1}{2}$), 15.9 (oc. $\frac{1}{2}$), 17.4, 18.2, 19.1 (oc. $\frac{1}{2}$), 25.0 (oc. $\frac{1}{3}$), and 35 (2).

CLEMENTS'S PIKE'S PEAK GROUP (C)

In 1919, Dr. F. E. Clements initiated this study of the Rocky Mountain zone by sending me nine sections of trees from the vicinity of the Alpine Laboratory, which is just south of the Cog Railroad above Manitou, at an elevation of 8,700 feet. He described the location of these trees as follows: Three yellow pines from north of track with a south exposure, three Douglas firs from above cabins with a northerly exposure, and three Engelmann spruce from near the brook, with a northeasterly exposure. These were actually cut and packed by Mr. C. W. Cherry, who later helped me at Tucson for a few months. One of the pines was defective and could not be used, and the remaining eight trees were averaged and plotted in a curve from 1783 to 1919. This was recently Hanned graphically, as shown in

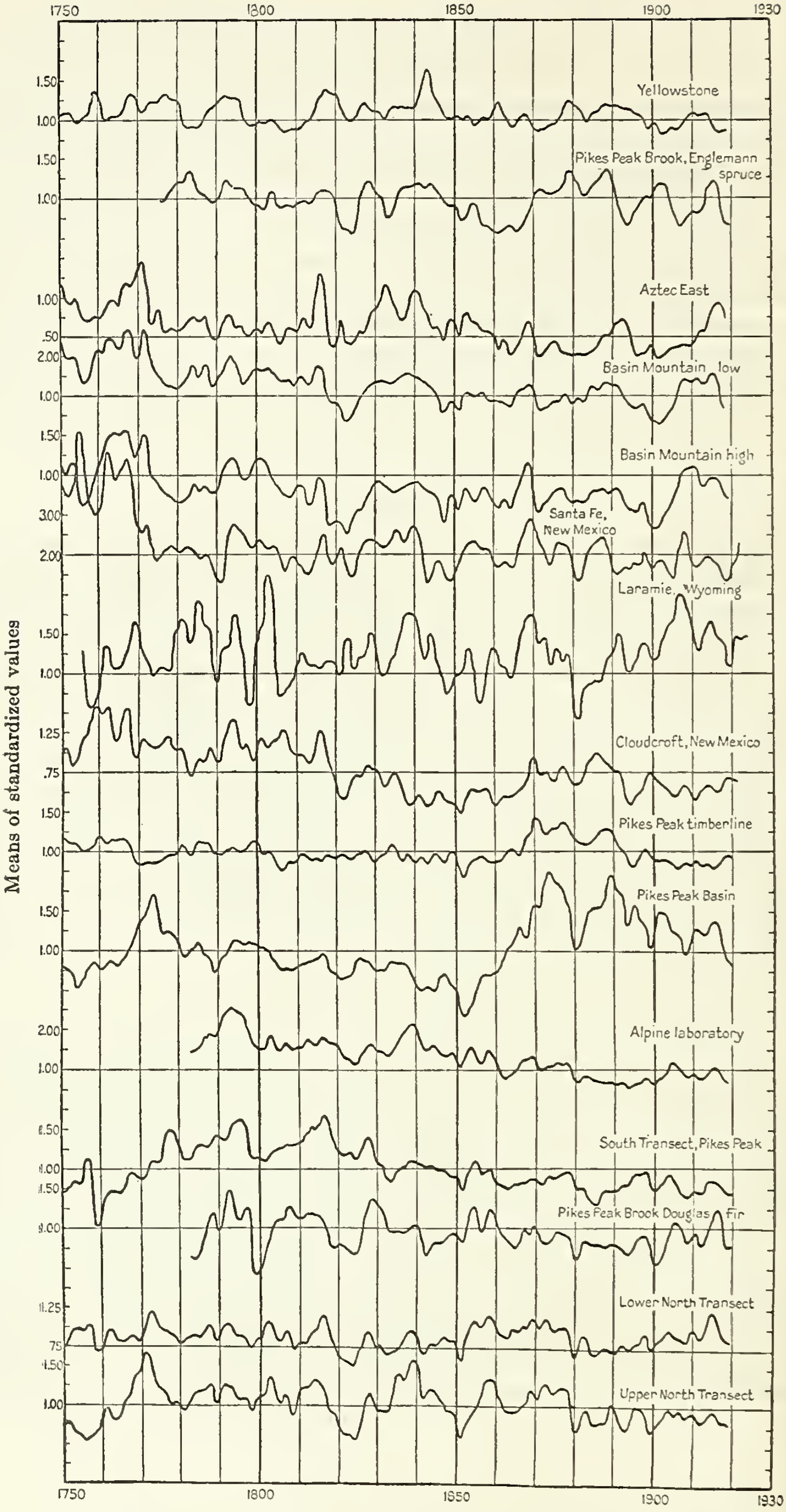

FIG. 5—Rocky Mountain zone, smoothed group curves

figure 5, and gave as cycles: 9.3 (2), 18.8 (2, $\frac{1}{2}$), and 34.8. So much material was obtained subsequently from that area that this group, with its informal treatment, has been retained as a check on the others. Without doubt the Douglas firs could be included with the yellow pines, but the Engelmann spruces should be kept separate. This will appear in the Brook group of Engelmann spruce (BES).

PIKE'S PEAK TIMBERLINE GROUP (PPT)

The first Pike's Peak group was obtained close to the Cog Road near timberline, at an approximate elevation of 11,500 feet. Naturally, the trees were not yellow pine. No. 1, a chip from a dead tree, had to be discarded, but five increment-cores, two in Engelmann spruce and three in fox-tail pine (*Pinus aristata*), proved good specimens. They were readily dated and were measured by Mr. Austin by the long-plot method. Each tree record was standardized and the curve, 1734 to 1919, was smoothed in the usual way. The portion since 1750 is given in figure 5. Its complacent character shows at once, yet it compares exceedingly well with the smoothed curves of groups 3,000 feet lower down the mountain. The cycles are 11.7, 14.0, 20.0, 22.6 (oc. $\frac{1}{2}$ or $\frac{1}{3}$), and 37. This group, therefore, does not classify well as of Rocky Mountain type, but its cycles are of the general western sort. One notes here the tendency of the double sunspot cycle to fall a little below 23.0 years; in the Arizona area it was usually a little above.

PIKE'S PEAK BASIN GROUP (PPB)

In making its way east after passing timberline, the Cog Road descends sharply into and then more gradually through a basin area to an outlet in Ruxton Creek, where the water-supply for the cities below is taken. The more level part of the basin has an altitude of about 9,500 feet, and here four borings were taken, of which three (PP 7 to 9) form the basin group. Mr. Austin measured these by the long-plot method. After standardizing, a curve, 1693 to 1919, was drawn and smoothed by graphic Hann; figure 5 gives the part since 1750. This has much larger variations than the timberline group and compares closely with the later groups near the Alpine Laboratory. The unusual feature in this group is the doubling of average growth after 1865. The cycles are 10.2 (2), 13.0 (oc. $\frac{1}{2}$), 20.0 (3, $\frac{1}{2}$), 25.6, and 30.7 (2, oc. $\frac{1}{2}$ or $\frac{1}{3}$). The absence of a 17-year cycle is not usual in this zone, but the presence of 25- and 30-year cycles is very characteristic.

UPPER NORTH TRANSECT GROUP (HNT)

The Alpine Laboratory has an elevation of about 8,700 feet, and near it are varying contours well worth testing. The various Pike's Peak groups, including those already described, were originally selected as a study in topography. After leaving the basin the Cog

Road descends sharply, following the bed of Ruxton Creek. The laboratory is situated on a small southern tributary, Jack Creek, just above their confluence. Dr. Clements has made extended ecological studies on a certain area, the Transect, which extends a half mile up the high, wooded slopes to the north and perhaps a third of a mile up the shorter and more barren slopes to the south. The north branch of this transect has very steep slopes in the lower part near this creek and the Cog Road, and gentler slopes above. So the collections there were divided into upper and lower groups. The upper group, PP 11 to 20, has an average altitude of over 9,000 feet and includes 5 yellow pines, 3 Douglas firs, and 2 limber pines. These 10 cores were measured by Mr. Austin, using the long-plot method. They were standardized, and the curve, 1655 to 1919, was smoothed as usual, and the part since 1750 is shown in figure 5. It resembles the neighboring groups very closely indeed. Its cycles are 6.8 (2), 8.6 (2), 9.3, 13, 17.2, 22.6 (2), and 34.5 (2, oc. $\frac{1}{3}$).

LOWER NORTH TRANSECT GROUP (LNT)

The lower group, PP 21 to 27, in the North Transect, was 250 feet below the upper, estimated in vertical height, which makes it about 8,800 feet above sea-level. Mr. Austin measured these cores also by the long-plot method, and the curve, 1644 to 1919, smoothed after standardizing, is shown (after 1750) in figure 5. The result shows a rather even curve, more complacent than the trees farther from the brook. It compares closely with the other group curves. Its cycles are 11.1 (2), 16.0, 20.4 (2), 21.3 (oc. $\frac{1}{2}$), and 40, which approximate but are not exact in their conformity to the Rocky Mountain cycles.

SOUTH TRANSECT GROUP (ST)

South of the Alpine Laboratory the slopes rise abruptly up to some very barren sand areas on Baseball Ridge. A collection of 10 increment-borings was made here with the help of Dr. Gorm Loftfield at an average level perhaps of 8,900 feet. Two of these are yellow pine, 6 are Douglas fir, and 2 are limber pine (*Pinus flexilis*). They cross-identified well and were measured by Mr. Austin and standardized. The curve 1570 to 1919 was smoothed as usual and the result (since 1750) is given in figure 5. It shows vigorous variations which make it probably the best representative curve of this Pike's Peak area. Its cycles also are entirely typical of the Rocky Mountain zone; 9.8 (2), 17.2 (2), 19.7 (3, oc. $\frac{1}{2}$), 25.2 (2), 31.1, and 34 (oc. $\frac{1}{2}$).

BROOK GROUP OF DOUGLAS FIR (BDF)

Ten trees were tested along Ruxton Creek near the Alpine Laboratory, with the purpose of forming a brook group and of learning whether the Engelmann spruce reacts to abundant ground-water in the same way as the yellow pine and Douglas fir. While dating the records, it was evident that the Engelmann spruce was giving a different story and could not be joined with the firs and pines. So the brook trees are separated into two groups, of which this one is made up of 4 firs and 2 yellow pines. One of these firs, PP–35, carries a dendrograph designed by Dr. D. T. MacDougal. The two yellow pines are only a few feet away, and these three trees are sometimes referred to as the dendrograph group; but they are themselves close to the brook and their records agree well with the other Douglas firs near by, so they make up part of this group. These six cores were measured by Mr. Austin, using the long-plot method, and after standardizing gave a curve from 1782 to 1919, which was smoothed in the usual way and is shown in figure 5. This closely agrees with the other adjacent groups already described, and with them (PPB, HNT, LNT, ST, and C) forms a collection of homogeneous groups which must represent this region exceedingly well. The cycles of the Douglas fir brook group are 7.5, 9.5 (2), 11.4 (oc. ½), 14.3 (oc. ½), 20.4 (2), 22.5 (2, oc. ½), and 39, a good Rocky Mountain set.

BROOK GROUP OF ENGELMANN SPRUCE (BES)

Engelmann spruce growth on the San Francisco Peaks in Arizona had been too complacent for use in climatic study, but on Pike's Peak four trees, PP 28 to 31, along Ruxton Brook, showed attractive variations and even exhibited weak signs of cross-identification among themselves. But when the curves were drawn, it was seen that their growth does not match the growth of the other brook species. The cores were measured by Mr. Austin by the long-plot method and standardizing lines marked on each individual tree-curve by the writer, as always. The resulting smoothed curve, from 1775 to 1919, shown in figure 5, presents marked variations, departing greatly from the typical Pike's Peak curve. Its cycles are 8.9 (2), 12.2 (2), 14.1 (2), 17.6 (½), 24.7 (oc. ½), and 34 (oc. ½). The 17-year cycle is characteristic of the Rocky Mountains, but the presence of a 14-year cycle and a probable sunspot cycle make this set resemble the cycles of the Coast zone.

CLOUDCROFT, NEW MEXICO, GROUP (CC)

Any real representation of the Southwest would be incomplete without specimens from New Mexico's summer resort, Cloudcroft, in the Lincoln National Forest. Accordingly, six good v-cuts from pine stumps were sent me by Mr. Dan Felts, forest ranger there. Three only could be used, and these, as Mr. Felts writes, come from the northwest quarter of the southeast quarter of section 23, township 16 South, range 11 east, New Mexico prime meridian. This is the extreme upper end of Nelson Canyon watershed, half a mile west and southwest of Russia, New Mexico. Mr. C. W. Cherry measured these specimens by auto-plot method. They were approximately standardized by assigning added weight to the slower-growing trees in forming the averages. The resulting curve from 1736 to 1920, smoothed by a careful geometric Hann and mostly shown in figure 5, presents strong variations which have much in common with the Pike's Peak curves. The cycles are 11.2 (oc. $\frac{1}{2}$), 13.4, 15.3 (2), 17.8, 22.1 ($\frac{1}{2}$ or $\frac{1}{3}$), 27.5 ($\frac{1}{2}$), and 35 ($\frac{1}{2}$).

SANTA FE GROUP (SF)

This group was collected on September 5, 1922, with the aid of Mr. B. Z. McCullough, who took me some 4 or 5 miles up the canyon east of Santa Fe, New Mexico. The trees selected had usually a north exposure and were in the general vicinity of the ranger station. They were chosen at considerable height above the brook, so as not to be influenced by it. All of the six cores were readily dated by resemblance to the Flagstaff series. Mr. C. W. Cherry measured these rings by the auto-plot method. After standardizing, he plotted their average in a curve from 1749 to 1921 and smoothed it by a careful geometric Hann. The result given in figure 5 shows excellent variations with distinct apparent similarity to curves of the Flagstaff area, but the cycles conform more to the Rocky Mountain zone, being 10.2, 11.9, 18.4 (2), 22.4, 27.5, and 35 (2, oc. $\frac{1}{2}$). The absence of a 14-year period places it with the Rocky Mountain groups, although the absence of the 17-year period is unusual in that zone.

BASIN MOUNTAIN UPPER GROUP (BMH)

The collection of this and the two following groups is due to the coöperation of the archæologists. In August 1919 I visited the Aztec ruins, New Mexico; thence Mr. Morris took me to Sullivan's saw-mill on Basin Mountain, in Colorado, nearly 40 miles north of Aztec and perhaps 15 southwest of Durango. The mountain has a perfectly flat top about a mile across, covered with pines. The saw-mill is 2 or 3 miles away, in the basin to the east. The pine trees extend down to the mill and a few scattered ones are found even lower down. Two v-cuts were taken from logs at the mill; five more were cut from stumps on the mountain-top before it got dark, and on the way down we cut the three which made the lower group, of which the last was cut by the light of matches long after nightfall. This division into upper and lower groups was made on account of varying water-supply in the soil. The date was August 13, 1919. Mr. J. F. Freeman measured all these specimens by the standard cathetometer method and the seven from the mountain-top have been combined without standardizing to form a curve beginning 1588 and ending 1919, which cross-identifies minutely with the Flagstaff tree-growth.

This curve, smoothed and shown in part in figure 5, distinctly resembles the Flagstaff curves in position of the more prominent maxima, but its cycles, 8.5, 16.8, and 35 (2), are characteristic of the Rocky Mountain zone.

BASIN MOUNTAIN LOWER GROUP (BML)

The three v-cuts in this group were collected August 13, 1919, as has been described in the preceding paragraph. Their actual location was on the upper easterly slopes of Basin Mountain, some 500 feet vertically below the top. Thus climatically they are in the same situation as the others, but with regard to soil moisture they are very different, for they catch a local drainage. In fact, the lowest of the three, No. H–29, had large complacent rings and could not be used. The two remaining ones average 50 per cent larger growth than the upper group. Mr. Freeman measured these with the cathetometer. The curve, not standardized, begins at 1700 and ends 1918. The smoothed curve from 1750 is shown in figure 5. The cycles are 10.5, 11.6, 13.4, 20.4 (oc. $\frac{1}{2}$), 22.7 (3), and 37, which resemble the Coast cycles.

AZTEC EAST GROUP (AE)

On inquiry, Mr. E. H. Morris found that there were Douglas fir trees nearer Aztec than the pines of Basin Mountain, namely, at a point some 20 miles east. Accordingly, early in 1920 he secured four specimens from there, H 39 to 42, which form this group. They showed severe drought effects in several places, which made the dating of the central parts uncertain, and accordingly later in the same year he sent me five more, H 65 to 69, which gave entire certainty to the dating. The earlier four were then measured by Mr. Freeman with a micrometer slide, and the curve, 1662 to 1919, drawn without standardizing (as was the case with several of the early curves) and smoothed, is shown in part in figure 5. As with the others from this region, it resembles the Flagstaff curves. Its cycles are 8.1, 12.4, 19.5, 24.0 (3), and 34.2 (oc. $\frac{1}{2}$), which resemble both the Flagstaff and the Rocky Mountain cycles. A later curve, using all these "Modern H" trees, gives cycles as follows: 8.2, 13.7, 18.8, 20±, 23.8, and 36.

THE COAST ZONE

BOISE, IDAHO, GROUP (BI)

This group is a set of 10 increment-cores sent by the forest supervisor of the Boise National Forest, in July 1923. They came from the southwestern parts of the forested mountains, some 50 miles northwest of the city. The growth is complacent, but the cross-identification of all 10 is good. Two of the trees cross-identify with some of the trees from Klamath Falls, in southern Oregon. These rings were measured by Mr. Austin, using the long-plot method, and represented dates from 1652 to 1922. The smoothed curve,

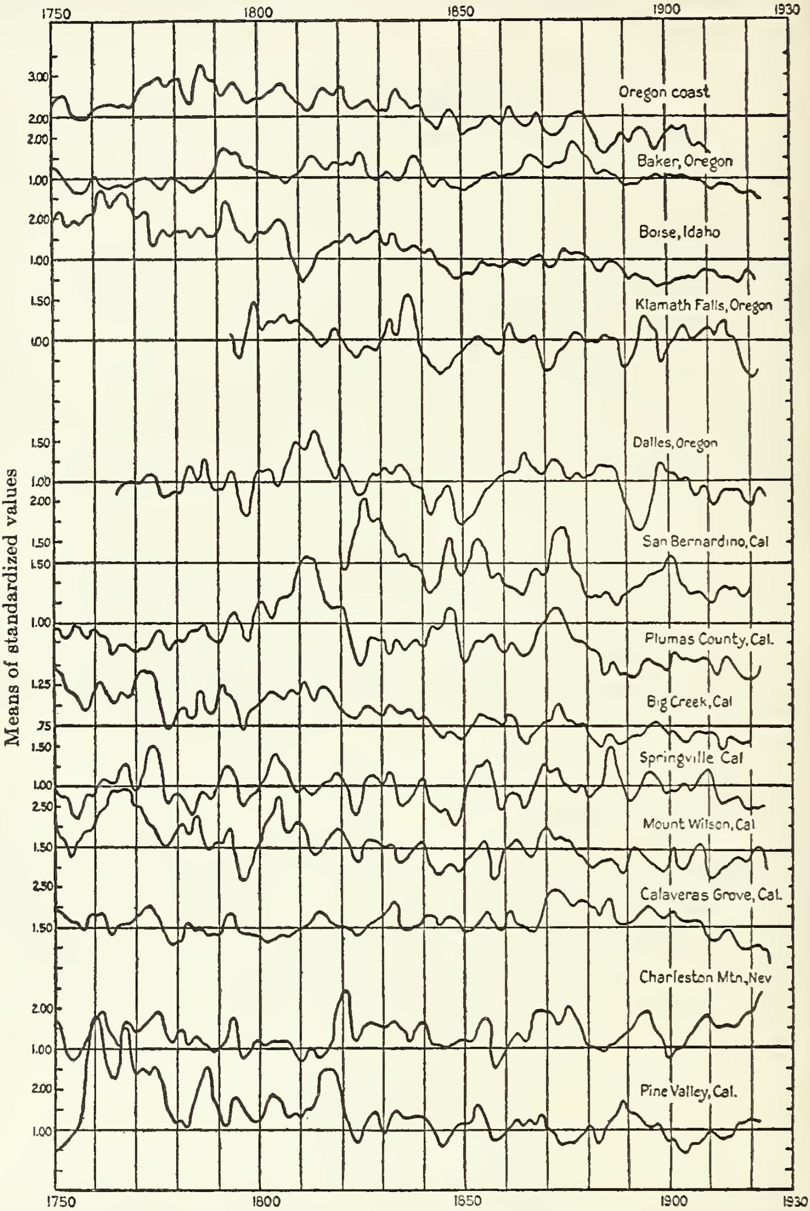

Fig. 6—Coast zone, smoothed group curves

shown in part in figure 6 herewith, when taken in its entire length, and especially when reduced to 3 specimens showing more variation, though complacent for short cycles, evidently has a long period of the order of 40 years. The cycles are 6.4, 11.6 (3, oc. ½), 17.2 (oc. ½ or ⅓), 23.0 (oc. ½ or ⅓), and 36. This strong emphasis on the single sunspot cycle, especially in the higher latitudes, is very characteristic of the Coast cycles.

BAKER, OREGON, GROUP (BO)

The higher parts of the pass between Baker, Oregon, and the Columbia River are pine-covered, and at distances from Baker varying between 60 and 90 miles 8 increment-cores were obtained. These are complacent, and the dating, though probably right, has not the certainty of the Arizona and Rocky Mountain pines. One core had to be omitted because it was erratic, probably from injury. There was some cross-identification with the Boise and the Klamath Falls groups. The rings were measured by Mr. Austin, using the long-plot method. The records were standardized and a curve produced extending from 1660 to 1924. This was smoothed by the usual graphic Hann and is shown in part in figure 6. It is a trifle less complacent than the Boise group and, like it, tends to show a long period of the order of 40 years. The cycles are 6.8, 9.1, 11.3 (2, oc. ½), 15.0, 21.8 (2, oc. ½), and 28.4 (oc. ½). These have some of the Rocky Mountain characteristics.

DALLES GROUP (DL)

The most beautiful part of the Columbia River Highway passes through the mountain range between Portland and The Dalles. On the west side of this range the rainfall is heavy and the vegetation profuse; the east side of the mountains is dry, looking out onto the arid areas of central Oregon. A narrow belt of yellow pine runs north and south along this eastern slope. This small group of three increment-cores came, therefore, from a point 8 miles west of the rapids in the river which gave the name, several hundred feet above the river on its very steep south side. The dating between these three trees was very satisfactory. The rings were measured by Mr. Austin, and the standardized curve from 1765 to 1924 was smoothed in the usual way and is shown in figure 6. This curve has a trace of similarity to those at Baker and Boise, especially in respect to the apparent long period and its phases, but its real conformity is with the California curves to the south. This group shows a profound depression from 1890 to 1894, which suggests fire or injury of some sort. The cycles are 7.2 (2), 12.6, 14.2 (3, oc. ½), 16.4 (2), 18.3, 22.5, and 35.

OREGON COAST GROUP (OC)

This is the group of Douglas fir described in Volume I, which came from the low coast hills 25 miles northwest of Portland, where the rainfall is large and the snows of winter very rare. No real likeness in rings or in smoothed curve (graphic Hann) has been found here to the groups farther inland. The smoothed curve is shown in figure 6.

The cycles are 6.8, 10.2 (2), 14.0 (3), 20.3 (oc. ½ or ⅓), 22.6 (2, oc. ½), and 28.3 (oc. ½). This is of mixed type and does not readily match any one of the three zones. Its 14- and 20-year cycles remind one of Arizona, but the 10-year cycle is strongly Rocky Mountain and the one close to 23 years is most common on the Coast. There is probably some relation between this set of cycles and its position close to the coast.

KLAMATH FALLS GROUP (KF)

This group of 12 increment-cores was received May 12, 1924, through the kindness of Mr. H. B. Rankin, supervisor of the Crater National Forest, near Klamath Falls, Oregon. They had been secured in that forest at an elevation of 5,100 feet above the sea. They cross-identified perfectly, and a few of them show likeness to some of the trees in the Boise and Baker groups. Mr. Austin measured all the specimens, using the long-plot method, and after standardizing, the curve was smoothed by graphic Hann and is given in figure 6. It presents no marked similarity to any other, though the Boise and Baker groups have real touches of likeness. Yet all the while its internal cross-identification was perfect and its smoothed-curve variations look entirely normal. Its cycles are 8.5, 9.6, 14.0, 15.5 (oc. ½), 19.5 (oc. ½), 24.2 (2, oc. ½), and 31.2 (2). This is a mixed set, but perhaps has a little more resemblance to the Arizona area than to the others.

A very fine 500-year pine record was sent me on July 23, 1925. The tree had been cut by the Pelican Bay Lumber Company in the same forest on the southwest quarter of section 35, township 29 south, range 6½ east, W. M., at 5,100 feet elevation and about 5 per cent east slope. This tree does not readily cross-identify with the 12 cores, and as it comes from a different place and is very old, it is reserved for future discussion.

PLUMAS COUNTY GROUP (CP*)

This group of 10 increment-cores from Meadow Valley was sent me by Professor Emanuel Fritz, of the agricultural experiment station, Berkeley, California. He says:

"Meadow Valley is eight miles west of Quincy, and the borings were collected in Township 24 North, Range 8 East. The region is very mountainous, but Meadow Valley is an ancient lake bed. The borings came from the southern border of the valley on a slope, less than 100 feet above the valley floor, elevation 4,000 feet. The water-supply is excellent and the soil is very rich in humus and carries considerable moisture. The forest growth is comparatively luxuriant. All the borings were taken in August, 1922."

They cross-identified well and were measured by Mr. Cherry, using the auto-plot method. They were standardized and smoothed by graphic Hann. The curve extends from 1551 to 1921 and the part since 1750 is shown in figure 6. It has a distinct similarity to the typical Sierra Nevada curve farther south. Its cycles are 6.7, 11.8, 13.7 (oc. $\frac{1}{2}$), and 28.6 (3), which conforms to the usual ones of the Coast zone.

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*"California pines," the first group of that species secured from California.

Professor Fritz also sent a partial section of pine tree from a point at about 5,400 feet altitude in Lassen County, near Susanville. This single tree-record begins at 1588 and ends in 1922. An analysis obtained in the usual way gives as cycles, 16.4 (2, oc. $\frac{1}{2}$), 20.2 (oc. $\frac{1}{2}$), 24.2 (oc. $\frac{1}{3}$), and 29.5.

CALAVERAS GROUP OF PINES (CVP)

The collection of this group of increment-cores at the edges of the Calaveras Grove of big trees on July 4, 1924, has been described in a previous chapter, page 53. The additional cores, taken near Murpheys, showed a larger growth average of 1.71 mm. as compared to 1.25 of the trees near the grove, but otherwise appeared to give much the same record, and all were included in one group of 14.

Mr. Hawkins measured these, using the long-plot method. An attempt was made in this group to standardize the individual records by using different gear ratios on the plotting instrument, but it was not felt to be entirely satisfactory, on account of the different average size of different parts of a single record; for instance, the larger central growth in early years of the tree can not be properly allowed for, and yet it is usually too good to discard. The average was undoubtedly improved by this change of gears, and there were so many trees in the group that it did not seem necessary to do any further standardizing. The mean of the 14 trees, 1621 to 1923, smoothed by a graphic Hann, is shown in large part (1750 to 1923) in figure 6. It is at once evident that this belongs to the inner collection of homogeneous Sierra Nevada curves. The cycles in this curve are 6.8 (2), 7.6 (2), 10.4, 14.6 (oc. $\frac{1}{2}$), 21.2 (2), and 30.2, which are of the Arizona type.

BIG CREEK GROUP (BC)

After the sequoia trip of 1919, it was realized that no pine records had been secured in California to aid in the cross-dating between Arizona and California. Accordingly, in 1920, at the request of Mr. Paul Redington, district forester at San Francisco, the ranger on Big Creek very kindly sent me five excellent v-cuts from pine stumps at an elevation of about 5,500 feet on Big Creek, a northern tributary of King's River. This river is just north of the General Grant National Park and the large areas from which the greater part of the sequoia records had come.

These pine specimens cross-identified among themselves exceedingly well, and there was no trouble in recognizing a number of Flagstaff dates in their rings. The average growth was nearly 50 per cent larger than the Flagstaff growth and many rings were immense. The specimens were measured by Mr. Cherry, using the auto-plot method. They were individually standardized by him and the resulting curve from 1719 to 1919, smoothed by geometric Hann, is shown in part in figure 6. It agrees exceedingly well with the Sierra Nevada collection, which extends from Calaveras Grove to Mount Wilson. The cycles are 8.4, 11.2 (oc. $\frac{1}{2}$), 13.5, 17.4, 21.7 (3), and 35 (oc. $\frac{1}{2}$), which classify as of Coast type.

SPRINGVILLE GROUP OF PINES (EP*)

The visit to Springville in early August 1925, and the collection of sequoia records, has already been described on page 54. The 10 pine borings came from elevations between 5,000 and 6,000 feet, that is, from Camp Lookout to the lower edge of the sequoias, about 4 miles away. Most of the pines had a local south exposure toward a canyon sloping toward the west. Some of these trees were on isolated points, where they could get no possible water except the rain or snow which fell immediately about them. Two could not be used; one was a magnificent 5-foot tree whose growth was too small to allow dating in the core and whose age therefore is probably very great; the other had an extensive fire injury and the rings were too erratic. Mr. Austin measured this group, using the long-plot method. The trees were standardized individually and the curve, 1720 to 1924, smoothed by graphic Hann, is shown (since 1750) in figure 6. It shows excellent variations agreeing most satisfactorily with the other Sierra Nevada curves between Calaveras and Mount Wilson. It is interesting to recall that the sequoias from Calaveras to Springville which show uniform cross-identification, to a considerable extent cross-identify with the pines nearby. The cycles classify in the Coast type as follows: 8.7, 11.4, 13.4 (2), 17.4 (oc. $\frac{1}{2}$), 23.1, 27.6 (2, oc. $\frac{1}{2}$), and 34 (oc. $\frac{1}{3}$).

MOUNT WILSON GROUP (W)

This group of 22 increment-borings, of which 8 are used, was made July 25, 1925, by courtesy of the Toll Roads Company and the Mount Wilson Solar Observatory, who gave permission to bore the trees. The top of the mountain, about 6,000 feet elevation, is a rough semicircle of ridge, convex toward the west and south, with the inner area in the form of an amphitheater of gentle slope toward the central drainage wash, which flows down past Strain's Camp. Sixteen trees were tested in this area, of which 8 are used, all yellow pines except one sugar pine and one Douglas fir, each of which gives apparently the same record as the yellow pines. The 6 Douglas firs tested on the road down the mountain were defective, perhaps in part injured by the road building.

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* Elster's pines.

The trees which could be used were in the triangle between the hotel, the Observatory museum, and Strain's Camp. One of the very best, No. 14, is a large tree in the fork of the gulch just above Strain's Camp, close to the upper hall. The ring record of this tree shows strong Flagstaff characteristics. This group was measured by Mr. Erickson, using the long-plot method. The records were standardized and a curve, 1725 to 1924, smoothed by graphic Hann, is mostly shown in figure 6. This curve has strong variations agreeing excellently with the Sierra Nevada curves. The cycles are 7.7, 10.4 (2), 11.2 (oc. $\frac{1}{2}$), 15.2 (oc. $\frac{1}{2}$), 17.1, 22.5 (2, oc. $\frac{1}{2}$ or $\frac{1}{3}$), 29.4, and 34 (2, oc. $\frac{1}{2}$ or $\frac{1}{3}$). These conform to the Coast type.

SAN BERNARDINO GROUP (SB)

The Forest Service in Los Angeles was kind enough to send me in 1922 some 13 increment-cores from the San Bernardino Mountains. Mr. Patterson measured the rings, using the auto-plot method. Five were omitted because they were too short; 2 were reserved because they did not agree well with the others, which formed a real group, and because there was a slight doubt of the dating before 1850; of these one shows an unusually regular 17-year cycle. The remaining 6 were combined into the present group. They were standardized and the curve, 1819 to 1921, smoothed by graphic Hann, is shown in figure 6. The very remarkable 23-year period is the most obvious thing in it. In fact, a search for older trees in that region might give some very interesting and valuable material. This periodic feature stands out because certain maxima which show well in the Sierra Nevadas to the north are here largely suppressed. The maxima which make this curve interesting are all present in the Sierra Nevada curves. The cycles here are 7.7, 9.8 (2), and 22.9 (4), the only case of assigning a weight of 4 to any cycle. These belong to the Coast zone.

CHARLESTON MOUNTAIN GROUP (CH)

The collection of this group of seven cores and one 500-year V-cut on July 18, 1924, has already been described on page 61. Saw Mill Canyon starts just north of the main peak and cuts to the east. The site of these trees is about 7,500 feet elevation and has something like 24 inches of rain. The canyon is narrow and composed largely of gravel terraces. Three trees high up on the very steep terrace bank to the south showed such slow growth that much of their records could not be dated, but the other specimens from the flat canyon bottom gave a fine agreement. The wash was dry. The 500-year stump was close to its north edge. The rings readily cross-identify both with Flagstaff trees and also with Sierra Nevada trees, thus corresponding to the intermediate geographical location. Mr. Hawkins measured them by the long-plot method, effecting partial standardizing by different gears in the measuring instrument. However, each tree-record was subsequently standardized in the usual way and the resulting curve, 1402 to 1923, was smoothed by graphic Hann. The part since 1750 is shown in figure 6. This curve is strongly of the Flagstaff type in the last century or so, except that 1818 to 1821 have large growth instead of small. The cycles are 7.3, 11.4, 14.4 (oc. $\frac{1}{2}$), 17.8 (3), 21.3, 25.9, 29.0, and 34. This is a Coast type.

PINE VALLEY GROUP (PV)

The Pine Valley here referred to is in the mountains some 50 miles east of San Diego, California, at an elevation of over 5,000 feet. The trees are more numerous at the southern end of the 2-mile valley, and of five increment-cores, three come from the vicinity of the summer resort there; one which could not be dated comes from the northern end and one comes from a very large tree about midway. Four were secured in the summer of 1923 and the undated one in August 1925. The rings cross-identify readily with those at Flagstaff. Mr. Hawkins measured the rings, using the auto-plot method. Standardizing was effected by reducing mathematically each tree-record to a set of departures from its own mean. The resulting curve, 1736 to 1923, smoothed as usual, is given in part in figure 6. This curve matches the Charleston group with great exactness and therefore is closely like the Flagstaff-type curve. The cycles are 6.6, 10.1, 14.4, 18.4, 25.2 (oc. $\frac{1}{2}$ or $\frac{1}{3}$), 32 (2, oc. $\frac{1}{2}$), and 35, which rather resemble the Arizona cycles.

MISCELLANEOUS GROUPS

The groups mentioned below have been collected for various purposes, but for one reason or another do not lend themselves to the study of cycle distribution. They are added here because reference has been or will be made to them.

SEQUOIAS

Calaveras group (CVS)—This group consists of two increment-cores, three V-cuts on fallen trees collected in 1924, and a tracing (recently measured and plotted by Mr. Austin) made by Mr. Manson in the 1880's. This was copied from an original tracing, which, with a separate copy, was filed in the library of the University of California. A copy was loaned to me by the Department of Agriculture of the University of California, and another was sent me by Professor C. F. Marvin, chief of the United States Weather Bureau. This "longitudinal" record is probably from the Dance Hall tree; it goes back to 621 A. D. The specimen which I collected from the "Old Maid" goes back to 525 A. D. My record from the "Father of the Forest" begins at 922 A. D.

Grant Park sequoias (GPS)—This group includes the 21 v-cuts made in 1915 and 1918 in the vicinity of the General Grant National Park. They are described in Volume I.

Topography sequoias (TS)—These are 12 small and usually incomplete radials collected in 1919 from the Grant Park region, giving the last 500 years of sequoia growth and selected with respect to topographic contours, ground-water, and so forth, to get the effect of these features on the size of rings.

Springville sequoias (SS)—These include two numbers, 22 and 23, collected in 1918, and 14 radials secured in 1925 from medium and very old trees at the old Enterprise mill-site some 20 miles east of Springville, California. These will be used especially in the formation of early tree-records and the attempt to date the prehistoric ruins of the Southwest.

COAST REDWOODS

Santa Cruz group (Z)—These are eight radial pieces of coast redwood collected February 20, 1921, some 15 miles north of Santa Cruz, California. These could not be cross-identified and so are not dated.

Scotia group (B)—These are 12 fine radials collected in early July 1925, at Percy J. Brown's lumber-mill, a few miles south of Scotia, California. These, too, did not cross-identify and have never been dated.

ARIZONA GROUPS

Flagstaff century group (FLC)—This includes 10 pines 500 years old, of which one extends back 640 years, all in the vicinity of Flagstaff. These will form the approach to the study of early pine records in the Southwest, which will include many semihistoric beam sections from the Hopi villages, and it is hoped from the prehistoric ruins also.

Flagstaff lava-beds (FLB)—These lava-beds are 16 miles northeast of town. Only two trees belong in this group, FL 48, inside the ring of lava, from which a 1-inch core was taken in 1920, and FL 51, just outside the lava ring, a v-cut from the stump. The former goes back to 1556 and the latter to 1598.

Prescott group (PR)—Nos. 1 to 70 were small incomplete v-cuts sent me by the Forest Service in 1911, described in Volume I. Nos. 71 to 75 are increment-borings made in 1924 to bring the Prescott rain comparison up to date. The records were not intended to go back before 1850, but some of them do.

OTHER WESTERN GROUPS

Pecos, New Mexico (L)—These are four radials from the forest near Pecos, New Mexico, sent by the Forest Service in 1920. They were needed for comparison with the prehistoric beams sent by Dr. A.

V. Kidder, who has been conducting excavations in the ancient ruins there. The rings in these specimens are rather erratic and only one gave a reliable record back to about 1720.

Raton, New Mexico (R)—This is a collection of three increment-borings secured near the highway over Raton Pass. Only one proved datable.

Nebraska (NEB)—This is a group of 12 sections from young trees sent by Mr. Jay Higgins, forest supervisor, at the request of Dr. F. E. Clements, from the plantations on the Nebraska Forest and from the native yellow-pine stands near the Niobrara Division of the forest. The three yellow-pine specimens all cross-identify nicely and give a record extending back to the middle 1880's. The jack pines, except one, are also reliable in dating and extend back to about 1907. The three Scotch pines extend back to about 1913, but do not cross-identify in a way to give confidence.

In the study of western cycles a group from Nebraska would be very valuable, but it should go back 100 years at the least for proper comparison with the other western groups. The above specimens, however, will be most useful in climatic comparisons.

Wind River, Washington (WR)—This group was collected June 20, 1925, at the Wind River Forest Experiment Station, Washington, a most favorable location on a tributary of the Columbia River, perhaps 75 miles from Portland. Five increment-borings were obtained, one yellow pine and the rest Douglas fir. Most of these were erratic in growth, perhaps from injuries, and one, at least, was too much crushed in boring. So the group was not used in the special study of western cycles.

NORTH AMERICAN GROUPS

American Arctic (AA)—These 21 sections, chiefly white pine and fir, came from high latitudes in the MacKenzie River area of northern Canada, by courtesy of Hon. Chas. Camsell and Mr. G. S. Hume, Department of Mines, Ottawa, at the request of Mr. V. Stefansson, the explorer. They were mostly cut in 1923. The interesting and gratifying fact is that they can be cross-identified for the most part and dated. The growth is usually very small and sometimes erratic. The 21 specimens are divided into three subgroups, as follows:

Subgroup	Average age	Average ring-size	Average diameter
	years	*inch*	*inches*
A. Nos. 1 to 6, lat. 60° N., South River group..........	57	0.034	4.08
B. Nos. 7 to 15, lat. 65.5° N., Lake group (Great Bear Lake)	85	.015	2.29
C. Nos. 16 to 21, lat. 66.5° N., North River group......	100	.020	3.94
Total, Nos. 1 to 21..............................	80	.022	3.3

These have been dated, but not yet measured. Considerable parts of all except one can be used, but there is a tendency to show very small compressed growth in the early years. No. 8, the exception, goes back to the neighborhood of 1700, but is too uncertain to use. No. 19 extends to about 1743, but can only be used after 1890. No. 10, beginning about 1792, can probably be measured. A fair record from 1800 will come from the Great Bear Lake region. The South River group extends to about 1835 and the North River group to 1860, with a single one to 1808. This valuable collection will be of the greatest help when the cycles over larger areas are studied.

East Wareham, Massachusetts (EW)—This group consists of some 21 v-cuts and increment-cores secured largely in 1921, from the region between Wareham and Sagamore Beach. The cross-identification is good in most of them, but injuries have affected a number and many are too short and only 8 are held as worth measuring. These will carry a good record to 1840 and a single one to about 1795. This last is from the "lone pine" which used to stand in the lane about half a mile southeast of the Onset Junction railroad station.

Mount Washington group—Two sections of very old black spruce trees from near timberline on Mount Washington have been kindly sent by Professor W. C. O'Kane, of the University of New Hampshire. These grew at about 4,000 feet elevation, were badly deformed, and were some 3 or 4 inches in diameter and about 275 years old. This is the nucleus of a valuable group.

Mount Desert, Maine—Three increment-cores were sent me in 1921.

NW. Pennsylvania group (PA)—This group of 10 v-cuts and 1 increment-core, 10 white pines and 1 beech, was collected May 20, 1922, from the logging camps of the Wheeler Lumber Company, by kindness of the manager, Mr. N. P. Wheeler, jr., in the higher parts of the mountains halfway between Pittsburgh, Pennsylvania, and Buffalo, New York. These cross-identify well and give a record extending back to about 1650. The beech shows favorable ring variation and gives promise of being a useful tree in such studies as these.

FOREIGN GROUPS

Brazil (BZ)—Two 6-foot sections of the South American pine from southern Brazil were measured by the auto-plot method in the Commercial Museum in Philadelphia. They had been cut about 1902 and were each close to 500 years old. They did not cross-identify, though the rings seemed clear and practically without error.

Tasmania (TS)—A section of King William's pine (*Athrataxis selaginoides* Don) from 3,000 feet elevation in the highlands of Tasmania, has been sent me by Mr. G. Weindorfer. It gives great promise of valuable cycle studies in the southern hemisphere.

VIII. ENVIRONMENT

This chapter deals with the effects of climate, topography, and other external agencies on ring-growth in trees; after which the point of view is reversed and the observed effects are listed as indicators of past climates.

EFFECTS IN TREES

CLIMATE

The common factor over large areas is climate. A heavy winter snowfall in Northern Arizona, which supplies abundant moisture for the trees there, extends over hundreds of miles and supplies abundant moisture in northwestern New Mexico, 225 miles away, or over on the coast mountains, a matter of 400 miles in the opposite direction. A dry winter in Flagstaff is usually dry in the other places also. Even at much greater distances the resemblances are enough to enable us to carry dates across in the trees.

Rings a climatic phenomenon—This is not surprising, for the ring is a climatic phenomenon. It begins with large, white rapid growth in the late spring when the sap flows. The usual time of this at Flagstaff (elevation 7,000 feet) is in late May or June and is well observed by the dendrograph, which magnifies the diameter of the trunk and shows its daily and hourly variations. In this arid climate, spring growth depends on the precipitation of the preceding winter, for the months of April, May, and June are exceedingly dry. In July and August come the heavy summer rains with a large run-off and little benefit to the trees. When the season closes, there is a gradual cessation of the activity of the tree, owing to lowered temperature and diminished water-supply. This causes the deposition of harder material in the cell-walls, producing in the pine the dark, hard autumn part of the ring and the protecting bark. The growth stops altogether in winter.

Small single rings—If the winter and spring have been unusually dry, the Arizona tree may stop growing by summer. The resulting ring will consist of a small white spring growth and a threadlike red outside growth. In old trees the ring may become microscopic or appear as a thickening of the red ring of the preceding autumn, and even disappear altogether in parts of the circuit of the trunk. In some extreme cases, sections could be found in which a ring or two is absent from the entire circuit. Very likely it was active for a time but not long enough to leave white cells.

Double rings—On the other hand, if the winter precipitation has been normal, the tree passes through the spring drought and reacts to the summer rains and displays additional growth. As a rule, near Flagstaff this late growth is very much less in width than the spring growth, usually between 10 and 20 per cent, rarely going to 30 per cent. When it is more than 15 per cent, it begins often to show a double effect, with its central part lighter than the red on each side. In extreme cases this autumn growth actually gets back to the color of spring wood and the growth becomes nearly white, thus separating off an extra red ring that is rarely hard to distinguish from the annual autumn red ring. The distinctive feature is that the false ring fades gradually on both sides, while the true autumn ring fades gradually on the inside but ends abruptly on the outside.

Doubling and locality—The trees near Prescott show an extraordinary number of extra rings, usually easily distinguished by the criterion just mentioned. Some trees there have extra rings unusually small and sharp and separated by very white tissue. Such rings are more difficult to recognize. Sometimes there was more than one false ring. In such cases it is evident that the storm is very important to the tree. At that elevation, 5,200 feet, the rainfall is much less than at Flagstaff, and each rainy season is more nearly a series of isolated storms.

The soil on which these Prescott rings grew is a disintegrated granite which forms a very efficient reservoir, holding abundant water with little leakage. The top of Mount Wilson is very similar in type of soil, though not in climate, for it has a single rainy season in winter. Double rings are practically unknown there. At the lower levels of the Santa Rita Mountains near Tucson the soil and also the climatic conditions are again similar to those at Prescott. The trees there depend on summer rains even more than at the northern mountains and the doubling character is more conspicuous and bothersome. Thus it is seen that doubling is a local climatic effect.

Doubling and age—Doubling is far more conspicuous in the earlier or "youth" rings of a tree when the trunk is rapidly increasing in size. These youth-rings are larger and less sensitive than the later rings. Of course, it is more apparent in large rings, and any tree which grows rapidly is more likely to show it. However, without specially investigating the point, one is inclined to think that young trees, being less sensitive than mature ones, are a little more certain to continue their growth into autumn and so do have more doubling than mature trees. This could be tested by the dendrograph on properly selected trees.

Doubling and summer rains—Since in double rings the space between the false ring and the outside of the real autumn growth is due to summer rains, it seemed possible that this segregated autumn growth might give a measure of the summer rains. This was called at the time "partial ring study." As far as the matter was carried, the autumn growth was found to be much more closely proportional to the spring growth and to the winter rains than to the summer rains. The matter is one of some complexity, because records of the rains themselves are extremely incomplete, owing to their local and torrential character and heavy run-off. As a result, the tree-records of such rains are local and seem of much less value at the present stage of their interpretation.

Doubles and cycles—In the early Flagstaff work there were two 500-year trees which showed a remarkable half sunspot cycle for nearly 200 years, beginning soon after 1400. One of these was especially perfect in this cycle, showing it with most remarkable regularity (see fig. 17 and Volume I, fig. 32). This tree also was full of double rings. It has suggested the general question as to the character of the record of trees which show many double rings. Is such a record different from those in other trees? So far the answer is thought to be negative, but there is further work to be done on this point.

Doubles and high altitude—As one studies the upper levels of the yellow pine, above 7,000 feet elevation near Flagstaff, the double or extra ring becomes less and less common. So far as tests go, it does not appear at all in the highest trees. In these higher trees the rings are more complacent, there is apt to be less pitch, and so less red color, in the autumn part; yet this autumn part shows a large proportionate size. Here probably the summer rains play less part in the tree's life, for they are too local and the run-off is too big. But the winter snows especially are too heavy, the ground stays moister, and falling temperature is more often the agent which stops the yearly growth.

Other trees—As stated above, the yellow pine in California shows very rare doubling. Douglas firs and sequoias practically never have it, but pinyon and juniper at the lower levels in Arizona are badly subject to it.

Large single rings—If rains in Arizona are abundant and well distributed, growth extends beyond the summer period. A good distribution here does not mean that they assume at all an even distribution, for in many years evident division into wet and dry seasons has never failed. In a long drought the summer and winter rains decrease and the spring and autumn rains disappear, sometimes entirely. In wet periods, summer and winter rains are heavy, and spring and autumn rains come every few weeks. In this latter event the trees carry their growing-season into autumn. Thus, without putting on any preliminary red ring, they show a wide growth of white tissue, ended in autumn by a dense, narrow red ring.

Rings in buried trees—In the vicinity of Flagstaff a considerable number of buried trees have been washed out at depths from 18 inches to 16 or 20 feet. The upper trees have rings of modern type, while the lower ones show enormous rings up to a centimeter in size. They exhibit two characteristics which go with larger water-supply than noted to-day in Arizona. The centers of the white parts of the youth-rings show sometimes a softening that gives an effect almost of an abnormal ring. And when the tree is old the red part of the rings is very massive and wide in proportion to the rest, and the ring sequence is subject to characteristic "surges" which are common in European and other wet-climate trees. In this surging there is considerable difference between largest and smallest rings, but the change from large to small or the reverse is gradual, so that the mean sensitivity is low, though the rings show strong variations. This sort of thing is very different from the habit of the living Arizona trees.

Certain small white needle-shaped crystals discovered in these ancient stumps were identified by Dr. F. N. Guild (1920, 1921) as the first observed occurrence of terpin hydrate as a natural mineral. On account of the location, it was named "Flagstaffite."

RAINFALL CORRELATIONS

If successive years were exactly alike, the rings would all be of the same size, with some alteration with age or injury. But successive years are not alike, and in their differences there are climatic factors which appeal strongly to the tree. In northern Arizona, with its limited moisture and great freedom from pests and with no dense vegetable population, and with the seasonal correlations above described, this controlling factor is unquestionably rainfall. This is entirely in accord with the rainfall comparisons given below.

Prescott growth and rainfall—This was worked out to 1908 in Volume I. Its insertion here is to call attention to figure 7, which gives tree-growth and rainfall at Prescott extended to 1923, with a new calculation of rainfall from growth, using the method described in the previous volume. The discrepancies in the last few years probably arises from the error of boring trees too near the roads, as was the case with the recent collection. The calculations and plotting for these curves were done by Mr. D. A. Hawkins.

Flagstaff tree-records and rainfall—The official Weather Bureau records at Flagstaff began in September 1898. Hence, there are very few years for comparison with tree-growth. A gain has been made by using fragmentary records beginning in 1888 and filling in the deficient months by estimation, using for comparison various records in other localities of northern Arizona, such as Holbrook, Fort Defiance, Prescott, and so forth. Practically all the precipitation after November 1 falls as snow, and hence that date is used as the beginning of the year in reckoning rainfall. But even so the total rain does not show a correlation with tree-growth. So, remembering that the torrential summer rains do not greatly benefit the trees, the year was divided, as it is naturally, into winter and summer precipitation, the former from November 1 to June 30 and the latter from July 1 to October 31. It was immediately evident that this removed the unexpected disagreement, for the winter values closely resemble the tree-growth, while the summer rains (averaging 10 out of an annual total of 23 inches) show no relation to the growth. This is shown in figure 8. Though the length of record is not great enough to test satisfactorily any formula for reducing rainfall to tree-growth, or the reverse, the evidence indicates that the same principle of accumulated moisture used in the Prescott correlation (Volume I, p. 66) applies here. The accumulated moisture curve for the winter precipitation at Flagstaff is shown in curve 4 of the figure.

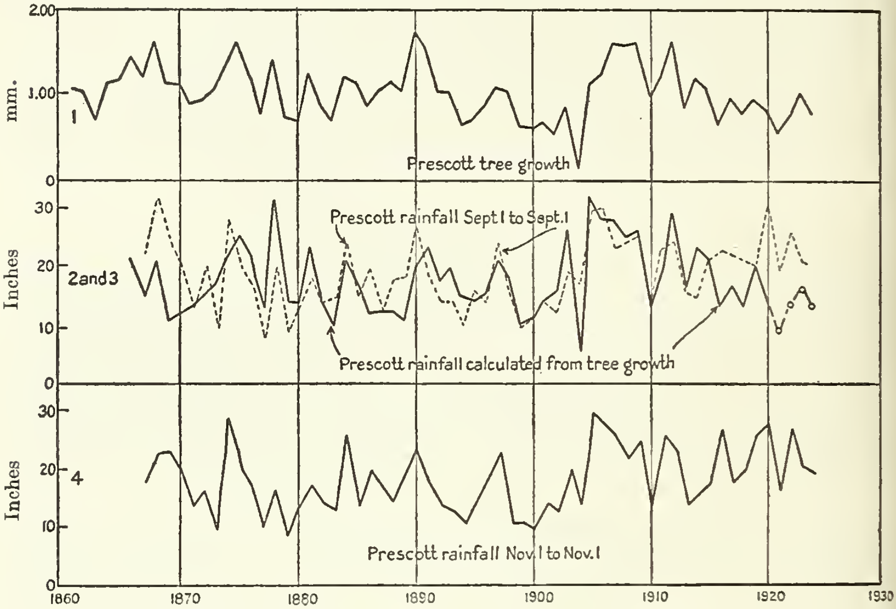

Fig. 7—Prescott rainfall and tree-growth

Flagstaff and Prescott difference—In the correlation between rainfall and tree-growth at Prescott, it was not necessary to segregate the winter rains for the purpose, because the correlation was apparent when using the annual total. But in the Flagstaff area the winter precipitation only can be used. Without doubt this difference arises from the topography of the country. Prescott is situated in the lap of the Bradshaw Mountains opening to the north and protected from the southerly summer winds, while the Flagstaff area is mostly on the south side of the lofty San Francisco Mountains, about which summer clouds gather more easily perhaps than at any other point in Arizona. The summer rains, especially near these mountains, are intense and local and are likely to destroy any correlation.

Arizona-California rain record—There is a further important advantage in using only the winter rainfall, namely, that such precipitation is essentially alike in Arizona and California. Since the coastal region has practically no summer rain to complicate the situation, the trees of Arizona become admirable recorders of California rainfall. In fact, it seems probable that these Arizona trees give a better record of California rainfall than do the California trees, so far discovered, though it is possible that very carefully selected sequoias will be found to give good records. This similarity in rainfall appears in figure 8, where the Flagstaff, Prescott, San Diego, San Francisco, and Mount Wilson rainfall curves are reproduced. From a meteorological point of view the similarity is not surprising, for the winter storms of northern Arizona cover very large areas and come from the coast with very trifling modification, giving precipitation in Arizona about one day later than in California.

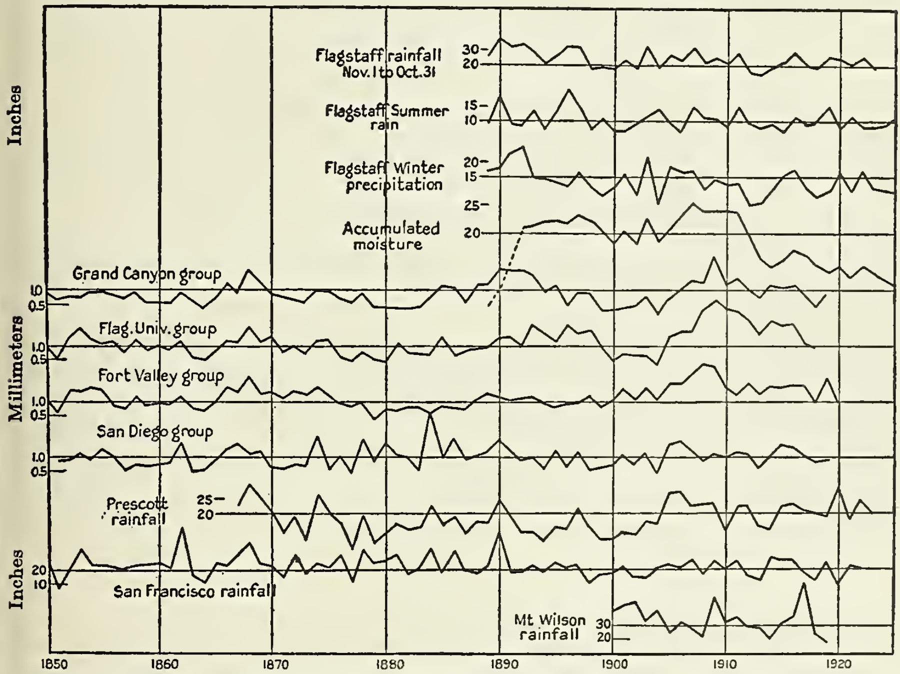

Fig. 8—Flagstaff rainfall and tree-growth, with comparison curves; the tree-growth shows close relation to winter precipitation

Cibecue drought record—Figure 9 shows the record of a single tree, J–3, as measured by the auto-plot method. It shows the droughts between 1870 and 1905 in a striking manner.

Sequoia growth and rainfall—The attempts in the previous volume to find a real correlation between sequoia growth and precipitation (p. 70) were not satisfactory. Figure 10 shows a decided improvement brought about by the high-level trees, D 1–5, corrected for gross rings and compared with rainfall at San Francisco. There seems to be a real relationship here, even though it does not yet equal the Prescott correlation.

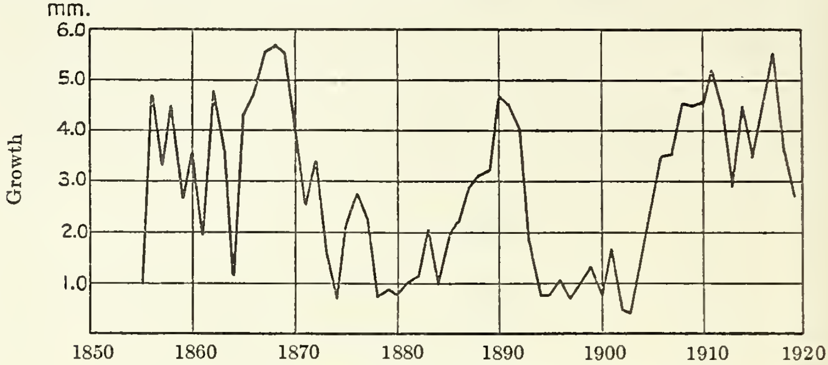

Fig. 9—Cibecue drought record traced directly from autoplot

Comparison records—There is yet much to be done in this comparison between tree-growth and rainfall, but the obstacle everywhere is the lack of rainfall records near the trees and over adequate periods of time. The five Prescott groups showed that in a mountainous country nearness is very important. Until very recently the nearest records to the sequoias were 65 miles away and at an elevation 500 feet lower. Colonel John R. White, superintendent of the Sequoia National Park, is greatly to be commended for starting adequate records there.

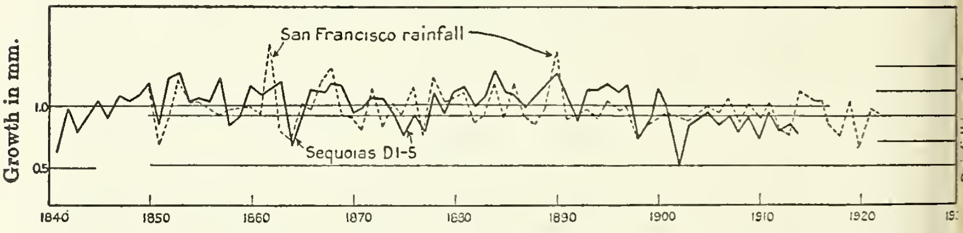

Fig. 10—Sequoia growth and rainfall

CONSERVATION

In the Prescott correlation, as discussed in Volume I, a conservation formula was applied, based on the idea that the accumulation of excesses or deficiencies in moisture affect the general activity of the tree. One might say that the trees respond each year to the amount of rainfall, but that their vitality is affected by the conditions for some years back. Thus, during the dry period from 1870 to 1905 or so, the trees responded each year to the fluctuations in rainfall, but with less and less spirit. This suggested that the conservation was in the tree itself.

Reversed conservation—In considering the details of smoothing curves of tree-growth (page 44), it seemed as if the derived value should substitute for the last of the several used in getting it, but as a matter of fact there appeared to be better agreement with rainfall when the derived value was placed in the middle, as in the graphic Hann, used so much in the western groups. This could only be true if favorable years affect the preceding year as well as the one after. And in the growth of trees that is not impossible, so far as we know at present, as will appear in the next topic.

Possible change in ring-size—The sapwood commonly holds much reserve moisture which can without doubt be drawn on for the needs of the tree and whose depletion can be changed to abundance when conditions are favorable. It may be that the conservation or vitality of the tree lies in this storage capacity. If so, it is entirely conceivable that the moisture condition of the growing layer affects the actual size of the rings near it, and that the ring-size is not absolutely fixed for several years after its growth. A first attempt to test this matter by borings in the same tree (FL–90) at 4-year intervals was not satisfactory, because the cores happened to show some slight irregularities in growth and were allowed to dry before measurement. Such variations as are referred to here might show in the dendrograph.*

Water-soaked rings—As an illustration of probable change in ring-size in dead trees from excessive water-content, reference is here made to the tests on a fallen sequoia described on page 24.

Repeated use of rain—Somewhat connected with the subject of conservation is the matter of the repeated use of rain. In separating the rainfall at Prescott into winter and summer records, the cycles of the winter rains at Prescott seem to be repeated in the summer rains, but the important ones in the summer rains do not carry over to the winter. This seems to mean that winter moisture lasts over locally to summer, but summer moisture mostly runs off or evaporates. This difference comes from the different types of storms in winter and summer. In the former, the storms come from the coast and clouds are continuous over an immense area. There is no chance for evaporation of any amount. On the other hand, in summer the sun is very powerful and each morning promotes evaporation over large areas between the scattered clouds. Storms come from the south and consist of immense masses of warm air laden with moisture. When these pass over a large mountain, they are thrust up in the air and start the storm. When there is not enough motion in the air to draw in distant moisture, clouds form directly over the valley, evidently composed of moisture from the valley. As the day goes on and the air gets a general motion, these clouds are carried forward and contribute to the rainfall in adjoining localities.*

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*Since the above was written, Dr. MacDougal has told me that he has detected with the dendrograph certain changes in the thickness of the two or three outer annual rings, depending on the temporary condition of the moisture-supply.

OTHER CLIMATIC CORRELATIONS

Several factors may enter into the tree-rings at the same time; for example, rainfall, temperature, length of growing-season, and direct solar stimulation. These may be isolated in two ways. We may select and study a special region, as northern Arizona, where nature has chosen out some one factor and made it preëminent, as rainfall. Or we may isolate certain relationships as in any other investigations, by using large numbers of observations, that is, many trees, and averaging them with respect to one or another characteristic.

Temperature—Undoubtedly temperature and the resulting length of growing-season enter tree-growth. At high elevations this becomes the controlling factor. Probably that is the reason the Upper Flagstaff group, FLH, shows departures from the usual curve of that area. But there is no evidence that temperatures affect the lower pine growth to any important degree, nor the sequoia growth, especially in the southern groves, for sequoias at the highest and coldest levels promptly respond to increased water-supply by enlarged growth, as in the case of D–31, referred to below in connection with sequoia topography.

Wind—Reinforced rings (see page 32) are interpreted as due to wind or other pressure exerted in a constant direction. In the prehistoric material from the ruins northeast of Flagstaff, such rings rather plainly indicate exceedingly strong spring gales from the west or southwest, if we can judge by conditions at the present day.

TOPOGRAPHY

The broad effects of topography were encountered and recognized in large measure while searching for the oldest sequoias. Almost at the start it was realized that size is far from a final indication of age, for nearness of water alters the rate of growth profoundly; for example, it is possible to assign 2,500 years as the approximate time it took the General Grant tree, which has no running water near it, to reach its present immense diameter of close to 30 feet. But about 3 miles west, near a running brook, is a stump which is over 25 feet in diameter, but is only about 1,500 years old. That rapid growth is the effect of contact with an unfailing source of water.

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*In Tucson we have perfectly clear views of the Santa Rita Mountains 40 miles south and 7,000 feet higher than the city, the Rincons 20 miles east, the Catalinas 20 miles north, also close to 7,000 feet higher, the Casa Grande and other mountains 50 miles northwest, and the Tucsons, 15 miles west, and so on. Cloud formations are easily seen.

SEQUOIA TOPOGRAPHY

In selecting specimens to settle a dating problem, in 1919, preference was given to trees at such distance from the obvious water-supply that the specific dependence of trees on the nearby brook could be tested. Thus from Redwood Basin, 15 miles east of the General Grant Park, a total group of 21 sequoias was obtained. The trees were scattered for a mile along this valley, whose slope faced the north. The upper or southern end is near the top of the mountain, but a spring supplies a small stream of water. The upper trees mostly had a very dry soil, while those below, some 600 or 700 feet in vertical measurement, had more level ground and greatly increased moisture. The average growth per century in the last 500 years was about 7.6 cm. The least was less than 4 cm. and the greatest was over 15 cm. The fast-growing trees were mostly close to the water-course in the lower basin. The average growers were mostly around the edges of the basin, while the slow-growing trees were chiefly at the tops of the slopes. Three larger growing trees close to the upper limit formed interesting exceptions. One was a youthful sequoia, only 700 years old when cut, and therefore naturally a fast-growing tree. Another at the very highest point was about 50 yards above the spring and undoubtedly tapped an underground flow of water leading to it. Its type of rings was very similar to those in the basin. The third exception had very large rings, but they were full of sensitive variations like the slow-growing trees nearby. This tree is probably over a pocket of water whose help increased its growth, but which failed in extremely dry conditions. It is evident, then, that with the sequoias moisture may control the growth up to a maximum fully four times as large as the minimum.

Ring-type and moisture—The type of ring and its adaptation to identification and study varies greatly with the moisture-supply. The large rings of the quick-growing trees are either very complacent, that is, of the same size for many years in succession, or gross in character, which means extraordinarily large rings here and there; and their whole grouping is apparently subject to slow surges in size as one glances across the sequence from center to bark. Gross rings in one tree have about an equal chance of appearing or not appearing in any other tree near by. Since gross and complacent rings have little individuality, it is not always easy to identify their dates, especially if the outer layers of wood have been cut away, as was usually done in felling the sequoias. On the other hand, the slow-growing, low-moisture trees are full of irregularities which may be recognized in tree after tree, thus rendering accurate dating a remarkably easy process. It is also immediately evident that these latter sensitive trees give short-period variations far more accurately and effectively than the complacent trees. These types, as well as the following one, are illustrated in Plate 3 and figure 3. Yellow pines in the dry climate of Arizona at so low an altitude that they have the utmost difficulty in getting water to prolong life become extraordinarily sensitive. In the same tree one finds some rings several millimeters across and others microscopic in size or even absent.

Mean sensitivity—Mean sensitivity, which expresses this different quality in the trees (page 29) depends in large part on the relative

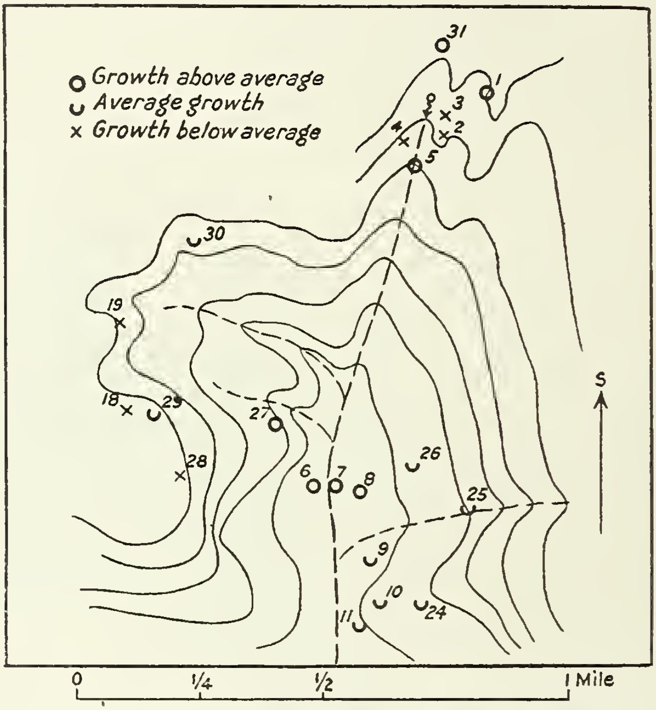

FIG. 11—Land contours and annual growth of sequoias in Redwood Basin

response of trees to climatic influence and so long as there are no large changes of ring-size due to injury, it gives a good criterion of climatic effects in trees. Such appears to be the meaning of figure 12, in which the 10 Prescott trees used in the original rain comparison are plotted with respect to ring-size and other features, including calculated mean sensitivity. The first curve shows them arranged in order of ring-size. The second curve, apparent mean sensitivity, estimated by inspection only, shows that such estimates may be too much affected by ring-size to be of value. Curve 3 shows that sensitivity is independent of ring-size. Curve 5 shows that correlation with rainfall had a slight

A. Sequoia topography, ridges; area of D–1, 2, 3, 4, 5, 18, 19, 28, 29 and 30

B. Sequoia topography, basins; area of D–6, 7, 8, 9, 10, 11 and 27

tendency to improve in smaller rings, and assuming some error in tree No. 69, mean sensitivity is an excellent indicator of a tree's accuracy in recording rainfall. Curve 4 hints that visual comparison between curves of rainfall and tree-growth was not very different from a mathematical correlation test.

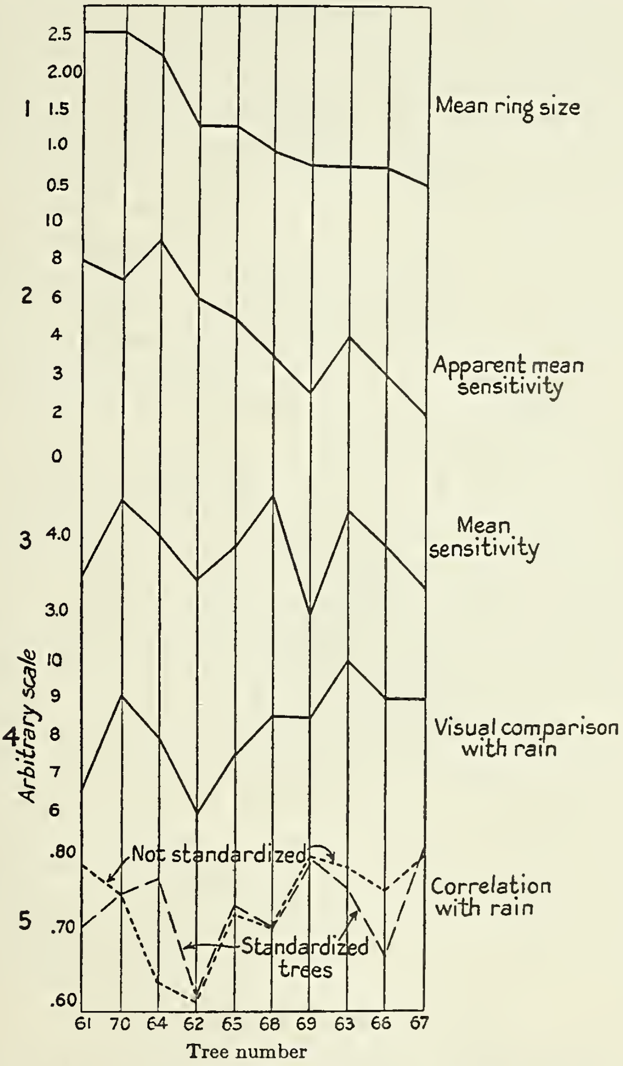

FIG. 12—Ring-size, sensitivity, and rainfall correlations, Prescott

Sequoia contours and cycle lag—Variations in the smoothed curves are much greater on the ridges than in the basins, where the water-supply is far more abundant. The complacent basin curves smooth out the shorter variations. A lag in the basin trees might be expected, since the water takes time in getting there from the higher surroundings. This has been sought by comparative analyses of basin and ridge trees. A lag of 3 years or more could have been detected, but none was found. There may, of course, be a shorter one.

PIKE'S PEAK TOPOGRAPHY

Pike's Peak contours—In collecting 47 specimens from the vicinity of the Cog Road on Pike's Peak in 1920, locations of test trees were selected with reference to contour and water-supply. The region lends itself exceedingly well to such tests. The valley bottoms are v-shaped rather than rounded, as in the sequoia basins. The sides of the valleys extend for great distances at a somewhat even slope. Water is far less abundant and the trees are left more to their own resources, as it were. The trees are scattered generally and one can get north and south exposures, stream contact, and other features. The soil material is relatively homogeneous compared to the Flagstaff region, where transition is abrupt from limestone to lava or the reverse, and hence tests are impeded on this account. However, on Pike's Peak the same tree does not cover all the conditions tested, and so each must be taken separately.

Yellow pines—Four groups had yellow pines in them, as follows, in order from north to south: Upper North Transect, 5; Lower North Transect, 2; Brook, 2; South Transect, 2. The mean ring-sizes in order were, 1.26, 1.60 (variable), 1.74, and 0.81 mm. The first and second of these showed considerable internal variation. The trees on gentler slopes or in small side-gullies had the larger mean growth, while trees on the very steep slopes toward Ruxton Creek had very slow growth. The largest growth was near Jack Brook, the two yellow pines there being some 20 feet above the water (and near the dendrograph tree). The smallest growth was on the South Transect, with its ridge topography, very steep slope, and sand areas indicating dryness.

The south-exposed North Transect, near the foot of a long mountain slope, has growth 75 per cent greater, and the brook has growth 100 per cent greater than the South Transect, which extends nearly to the top of a low, dry ridge. The extra brook growth is obviously a question of water-supply. So we infer that the added growth on the North Transect is due to moisture-supply also, and from the similarity to the Flagstaff area in some prominent features of the tree record, this better moisture-supply comes in the snows of winter. This has been considered in some detail, because the Douglas firs next considered give similar results.

Douglas firs—Douglas firs occur also in the same four groups: Upper North Transect, 3; Lower North Transect, 3; Brook, 4; and South Transect, 6. The respective mean growths are 1.09, 0.99, 1.20, and 0.43 mm. The apparent strong effect of slope in different parts of the North Transect appears again here and emphasizes the value of further work directly on that point. The growth on the North Transect is 142 per cent greater and at the brook 179 per cent greater than on the South Transect, and the same inference prevails as with the yellow pines.

Limber pine—Limber pine (*Pinus flexilis*) occurs in the three transect groups and the basin group at 9,500 feet. Three trees in the basin have a mean ring-size of 0.69 mm. The others of two trees each have 0.93, 1.02 (variable), and 1.00 mm. (variable). Thus, we can not make conclusions from the data on this tree, except that the reduced growth in the basin, 9,500 feet elevation, is very likely a result of temperature.

Engelmann spruce—Two specimens of this tree in the timberline group, 11,500 feet, give a growth of 0.95 mm., and four specimens at the brook give 1.16 mm. This difference is quite as likely to be temperature as moisture.

Fox-tail pine—Three trees of this species, *Pinus aristata*, were included in the timberline group, with an average growth of 0.63 mm.

Age correction—No age correction has been used in these figures, but as the selection of trees uniformly favored the larger and older ones, it is not likely that such correction would materially alter the results.

Summary—The area tested on Pike's Peak lies on the east slopes, chiefly below the basin. The pines and Douglas firs here show evidence that water is the prominent controlling factor, the pines having somewhat larger growth than the firs. The limber pines tested had an average growth between the other two, but were variable and, except that they give the same tree records as the others, there was no decisive material regarding their sensitiveness to moisture-supply. A single group of fox-tail pine gives a similar curve. Engelmann spruce had a larger growth at the brook, 8,700 feet, than at timberline, 11,500 feet, and its ring record is far different from the other species tested. Nearness to running water greatly increases growth in all the species, and apparently in the yellow pines and firs does not interfere with their success as climatic recorders.

SAN FRANCISCO PEAKS AREA

These beautiful peaks, 12,760 feet high, 10 miles north of Flagstaff, have the rounded mass of an ancient volcanic cone, with the huge outlying spread of Elden Mountain (9,000 feet) stretching off to the southeast. They are surrounded by pine forest for miles in every direction and give favorable opportunity for certain tests.

Altitude effect—Two groups, all yellow pines, may be compared to get an idea of this effect, namely, Fort Valley, at an elevation of 7,300 feet, at the southwest base of the mountain, and Flagstaff High group, at 9,000 feet, directly up that same southwestern slope. The first effect of altitude is an increase of mean ring-size from 1.10 mm. to 1.95 mm. resulting without doubt from the increase of precipitation at the higher point. The rings themselves of the higher group appear far more complacent, but can be dated in terms of the Flagstaff series. In comparing the smoothed curves of the two groups, the variations (those which become conspicuous in the cycle plots) decrease from 34 per cent at Fort Valley to 25 per cent in the upper location, and at the higher point lose much of their resemblance to the other smoothed curves of that region. On comparing the cycles one finds at the upper station the 17.3-year length, which is very rare in the Arizona area. It is more common in the Rockies and on the northern coast.

Shadow—As previously explained, mountain shadow is an expression which here refers to the side of the mountain away from the direction from which storms usually approach. It is, of course, on the east side of the San Francisco Peaks, since the winter storms come from the west and southwest. Two groups were taken to the east and northeast of the peaks; the shadow group (SH) close in at the foot of the steep eastern slopes at about the same level as Fort Valley, and Flagstaff Northeast group (NE), about 7 miles farther out from the mountain center and at the edge of the pines at an elevation some 500 feet lower. The ring-sizes in the SH group is 1.52 mm. and in the NE group 1.17 mm. The cycle variations of the former are about the same as FV (34 per cent), but the corresponding variations of NE are near 70 per cent. On examining the smoothed curves each seems to be free from short interfering cycles, and perhaps this is its special quality. The difference between them appears to be a question of water-supply, which is abundant very close to the mountain, but rapidly decreases to the east. This same characteristic of relative freedom from short-period cycles appears in the Lower Rim and the Cibecue groups and in the Charleston Mountain group.

Soil and bed-rock—Many of the Flagstaff groups grew on soil that was not distinctive. The first, for instance, was on deep soil formed by an outwash fan from Woody Mountain, which is igneous rock. The 500-year trees of FLU grew on a considerable soil over limestone. Probably the old group at Lake Mary, whose curve is given in Volume I, page 26, illustrates best the effect of this limestone soil. Its mean ring-size is about 0.75 mm. It shows rather stronger variations than the FL curve. For comparison, a group of two trees at the Lava Beds, 15 miles northeast of town, may be quoted. These trees were about 350 years old and show large growth when the trees were small and then a very long continuance of uniform small growth (0.50 mm. in one and 0.75 in the other), with slight variation. Lava soil of this sort is full of clay which is formed by decomposition of the rock. It is therefore water-tight compared to limestone soils. Hence, moisture caught in the former stays in place and produces a uniform tree-growth, while moisture entering the limestone soils readily passes away from the roots. The growth over limestone has larger percentage variations with better climatic relationship. This confirms the reference to this topic in Volume I, page 22.

Soil-moisture gradient—It is possible that a criterion of this difference could be found by the vertical soil-moisture gradient. Certain species of pine can grow in very wet land. In such cases the soil is wet at the surface, then soaked, and then full of water as one goes down a few feet. Tree sections occasionally appear which show an enormous increase in growth on draining such land. At an eastern point (Cape Cod, Massachusetts) the surface soil near the pine trees is sandy and below that are moist glacier gravels, down to water at 20 feet. In contrast with this, the trees around Flagstaff grow mostly on a thin layer of soil, perhaps 2 to 10 feet, upon impervious, igneous rocks, or upon porous and cracked limestone. Over the igneous rock is often a layer of clay. During a large part of the year one may dig about the tree, or near the tree, and find the ground apparently dry. Clays and volcanic rocks hold layers of moisture for a considerable time, but the soil over the limestone, as observed in some cases, gets drier and drier as one goes down. The average soil-moisture gradient, therefore, seems promising as a help in determining certain controlling factors in tree-growth.

Root conditions—Mr. G. A. Pearson, director of the Southwestern Experiment Station, has very kindly supplied data regarding depth of the root systems under certain trees near Flagstaff and per cent of available soil-moisture, as follows: The greatest depth attained by tree roots is usually around 4 feet, but only a few of them reach this depth; the great masses of roots are found in the upper 2 feet. In the case of spruce, very few roots are found below 1 foot in depth. These measures cover the woodland (cedar), yellow pine, Douglas fir, and Engelmann spruce. In his bulletin entitled "Natural Reproduction of Western Yellow Pine," a series of graphs shows the available soil-moisture in per cent of dry weight of soil, for the summer months, including May to September. At 6 inches in depth the amount for cedar and yellow pine varies from 1 to 9 per cent, and for the other trees about twice as much. At 12 and 24 inches of depth the amount for pines and cedars is between 5 and 0 per cent, and for the other trees about twice as much. The precipitation curves during the same seasons, 1918 and 1919, show that rainfall in the preceding months is felt by these trees at 6 inches, and by the high-level trees, fir and spruce, at 12 inches of depth, for at such levels the rainfall is greater, but at 2 feet only the Douglas fir shows it.

CHANGING CONDITIONS

The preceding topographic conditions are constant and their effects are sought by comparing trees in one location with those in another. The results are practically constant in any one tree. But changing conditions produce internal alterations in each tree and may often be recognized in the ring record after allowing for the normal change of ring appearance with age.

Shade—The Vermont hemlocks from the edge of Mount Ascutney, near Windsor, showed a doubling of yearly growth about 1808, due probably to cutting of adjacent trees at that time (Volume I, pages 41, 42).

Drainage—A small section of Scotch pine in the Berlin Museum shows minute rings for some 40 years and then suddenly the growth is quadrupled. As the history of the tree showed, this was caused by draining the very wet land on which it grew.

Soil deficiency—A very interesting relationship was recognized by studies in Chaco Canyon in 1926. For 10 years it had been noticed that certain prehistoric or early historic trees showed normal growth to a very good size and then rather quickly the growth dwindled down to a great number of microscopic compressed rings from which there was no recovery. In human language, the tree starved to death. Some of these specimens came from Chaco Canyon and a number came in 1926 from Wupatki, a ruin 35 miles northeast of Flagstaff, in the region of the Lava Beds and volcanic cinders, which suggested showers of volcanic ashes as a means of killing forests. But on the bare rock mesas about Chaco a few pines were found in favorable spots where a little soil covered the bed-rock. Some were dying, some dead, and a very few in good condition, but most of them showed the compressed rings for the last 50 or 100 years. Evidently there was enough soil for small trees, but not enough to support full-grown trees, and the shallow beds of soil were drying out and in many cases blowing away. One small pine in bad condition had 2 feet of horizontal roots bare before any of them were covered by soil. This lack of soil and change in its condition, then, is the common cause of that sort of outer compressed rings in this arid area.

Close grouping—A test for the effect of close grouping of trees was made on the Fort Valley group. These effects have already been described in connection with tree selection, page 12, and eccentricity of ring-growth, page 22.

Injuries—The injuries chiefly recognized in the western groups are fire and lightning-scars, already referred to in the selection of trees, page 14.

Pests—This topic is a recognition that such effects are of great importance in the general consideration of tree-rings. Where moisture and sunlight are abundant and vegetation is densely crowded and competition is intense, as in wet-climate forests, many individuals must perish, and pests are largely the agent. Climatic conditions influence these pests and we find therefore climatic variations in the trees injured by them, but such effects are apt to be more hidden and less clear and direct than in the dry Southwest, where the trees are isolated and rainfall is the controlling factor. Pests, of course, attack the trees in different ways, but when the growth is seriously interfered with the rings show diminished size and may disappear, and abnormal growths may enter.

ENVIRONMENT INDICATORS

The preceding pages of this chapter have dealt with the effects in tree-rings of various exterior forces; the present paragraphs are intended as a brief introduction to the general reversal of this process, namely, estimation of exterior conditions by internal evidence in the trees. So far as rainfall is concerned this is not new, for most of the work done by the writer has had that purpose as its central theme. But in approaching the study of prehistoric and geologic material, the general consideration of all information contained in the rings becomes more and more important. So long as one can apply the principles of cross-identification, it is easy to isolate the climatic effects, for climatic effects prevail over large areas for a short time, while topographic influences modify the growth-rates in small areas more or less permanently. Thus, as the use of groups of trees becomes less and less possible in studying climates more and more remote, the separation of climatic from topographic features requires notice to be taken of all indicators of environment found in the trees. Without any pretension to completeness, the following classification paves the way to a future study of this interesting subject.

EVIDENCE IN INDIVIDUAL RINGS

This varies in different species, but in the yellow pine a widely double ring means a double rainy season, especially if habitually recurring. Narrow and indistinct doubles and multiples probably mean the same, but in the extreme, multiple rings may refer merely to individual storms.

Average ring-size—This reflects water-supply, which consists (1) of rainfall modified by continent, mountain ranges, latitude, and altitude; (2) of ground-water, or secondary rainfall, modified by drainage contours and kind of soil.

EVIDENCE IN SINGLE TREES

Ring-type—Ring-types are: (1) complacent, meaning reasonably sure water each year; (2) complacent surges, meaning some slow variation in the complacent type; (3) sensitive, meaning limited water-supply from lessened rainfall and greatly diminished ground-water; (4) shadow or sensitive surges, meaning very great variations in slow-growing trees, such as come near the lower (dry) margin of the forest; and (5) erratic, meaning immense variations in water-supply, causing some rings to be omitted, while others are very large.

Missing rings—This occurs more often in old age of the trees and on very dry ridges, where the moisture is not likely to stay in the ground nearby.

Merging rings—These occur in the pines in dry periods. It does not usually mean close grouping. It occurs normally in the junipers and pinyons without close grouping. It probably does not usually mean close grouping in the big sequoias, but in coast redwood it does indicate it.

Gross rings—Gross rings in the sequoias are understood to mean root success with a slight climatic relationship, and to point toward certain variable conditions of grouping.

Lightning scars—Lightning scars are easily recognized in the tree section, but not in the core. They are climatic and occur in torrential summer-type storms.

Fire injury—This also is easily recognized in the section. Such fires are usually started by lightning and so become climatic in interpretation.

CHANGING RING-SIZE

The change with age is always conspicuous in the diminishing size from center to back. Rings growing smaller and then larger to a marked degree, in Arizona, mean drought. Badly compressed outside rings mean shallow and perhaps denuded soil. Probably soil denudation is better indicated when the compression lasts 50 or 100 years. Drainage of soil and relief from too much shade are of rare occurrence, but when they do come, are recognized by a very considerable change that is fairly quick and practically permanent. Reinforced rings mean wind whose season of occurrence may sometimes be estimated.

Climatic variations—Outside the various effects mentioned above, the further variations from year to year are mostly climatic. If several trees over some area can be cross-identified, it helps in the climatic interpretation. But the normal average tree in all ages, judged from large numbers of prehistoric beams and many fossils examined and measured, is practically free from other disturbances, and most of its variations, apart from age changes, can be taken as climatic. So also the smoothed curve and its cycle analysis tell a story of climatic variations.

IX. CYCLES

CYCLE ORIGINS

It is now generally recognized that certain small climatic variations are caused by changes in the sun. The study of tree-growth in this volume, and especially its correlation with solar cycles described in this chapter, provide the motive for seeking in the sun the real origin of larger climatic cycles and in the trees a detailed history of the effects of such cycles on organic life.

SOLAR THEORY*

Nature of sunspots—The work at the Mount Wilson Solar Observatory and elsewhere shows that two-thirds of the sunspot groups are dual, with a leader and follower in the direction of daily rotation. These are connected below the apparent surface of the sun and form the two exposed ends of a partial vortex-ring. The brilliant work of Hale has shown that during the recent sunspot cycles the leaders in the north and south hemispheres have exhibited opposite magnetic polarity and that during the two minima under observation, 1913 and 1923, the polarity reversed between the two hemispheres. This suggests a double sunspot cycle as the fundamental period. Hale (1926 to 1927) finds evidence that this polarity results from direction of rotation in the lower parts of the spot. Lighter gases in the upper and thinner layers of the solar atmosphere are sucked downward into the spot. Their direction of rotation resembles usually the rotation of storms on the earth and so is independent of sunspot minimum.

Periodicity theories—No recent advance has been made in explaining the periodicity of sunspots. The weight of evidence favors internal causes; for example, the polarity phenomenon and the "butterfly" diagram (by Maunder; it refers to the continued decrease in mean latitude of sunspots, as each cycle begins, reaches maximum, and ends) both point to internal causes. The possible extension of solar cycles back into geologic ages is more agreeable with an internal cause than with a meteoric hypothesis, using a swarm subject to perturbations and possible dissipation. On the other hand, there is a possibility that several cycles will need explanation, and it is hard to think of several mechanical pulsations in the sun going on at the same time. Mechanical disturbance between a dense core and a lighter shell have been the foundation of some thought on this subject. Snyder and others have been at work on a theory involving atomic energy. This might be called chemical pulsation.

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*Continuing a related topic in Vol. I, p. 84.

Turner's meteor-swarm theory has the merit of simplicity, since it merely becomes an extension of the accretion hypothesis (Chamberlin and Moulton) and offers many choices in periods. Perhaps size and shape of a meteor swarm could be invoked to explain crudely the butterfly diagram, but it is exceedingly difficult to reach with this theory the polarity and rotation of spots.

Short-period cycles in sunspots—An analysis of monthly sunspot numbers since 1750 gave a number of possible cycles, of which 7.9 months and especially 10.5 months were the best. The former of these is the period required by a meteor swarm to pass in a very elliptical orbit out to the orbit of Mars and back to the sun. The latter is the period a swarm would have with aphelion near the inner asteroids. The various periods noted in monthly sunspot numbers were found to be multiples of 35 days, which is very nearly the sidereal time of polar rotation of the sun (Abbot, 1925, p. 100). But to the present time no one has found any satisfactory evidence of planetary influence in the formation of sunspots, and this coincidence may be accidental. If there were a tidal effect from any planet, it would presumably take place twice in the solar rotation.

Solar rotation—Adams and others have applied the spectroscope to solar rotation at different latitudes and find sidereal periods for average surface rotation as follows: latitude 0°, 24.6 days; 30°, 26.3 days; 60°, 31.2 days; 80°, 35.3 days. High levels in the solar atmosphere rotate faster at all latitudes.

Radiation—Abbot (1925) has done important work upon radiation, and now has an accurate record of the solar constant from 1918 on. The values passed below normal in 1922 and stayed so during the sunspot minimum of 1923. With the beginning of the new sunspot cycle this constant has come back to normal. All this change seems to be a correlation with the sunspot cycle, with radiation 3 per cent above normal at the maximum activity. However, this is subject to sudden brief decreases, reaching even 10 per cent, when unusually large spot-groups are about one day past the sun's central meridian.

Ultra-violet radiation—Pettit and Nicholson (1926) have constructed a recorder of ultra-violet radiation (which has a powerful effect on plant life), using a thin silver film as screen and producing galvanometer deflections by a thermo-couple. The variations follow the sunspot activity with accuracy and at the same time exhibit a far greater sensitiveness to its changes than found in the solar-constant records, reaching perhaps 80 per cent difference between readings at times of maximum and minimum sunspot activity. The instrument promises to be of unusual value. Perhaps in this way will come the solution of a problem formulated years ago on finding the remarkable solar records in trees around the Baltic Sea.

TERRESTRIAL REACTION

Radiation and terrestrial temperatures—H. H. Clayton (1917 to 1926), while in the Argentine Republic, began using daily reports of the solar constant wired from Calama, Chile, in prediction of weather conditions for the succeeding 10 days over northern Argentina. This work he is continuing over parts of the United States in collaboration with C. G. Abbot, of the Smithsonian Astrophysical Observatory, under whose direction the solar-constant measures are made. Such prediction is based on direct effects in temperature observed in the two weeks or so following changes in the solar constant. Though still not accepted as conclusive by some (Marvin, 1925, etc.), the abundant tests already made seem to the writer to indicate a positive link in the chain of solar influence and terrestrial reaction. The full set of reactions as they spread over the earth is doubtless incredibly complex, and this appears to indicate something of the way the larger effects begin.

Radiation and drought—Dr. F. E. Clements (1921), who is working on the relation of drought to sunspot numbers, found from the rainfall records that when the relative numbers exceeded 80, a drought period of two or more years followed in the western United States.

Electrostatic reactions—The electrostatic charge in the atmosphere, earth-currents, and other electric conditions show response to solar activity. Dr. L. A. Bauer, of the Department of Terrestrial Magnetism of the Carnegie Institution, has done extensive correlation work (1923) and considers that terrestrial magnetic conditions vary with "agitated" solar conditions perhaps, rather than merely with extreme solar departures from the normal. Dr. Fernando Sanford, at Palo Alto, California, is making extensive records of atmospheric electricity and earth-currents and finds solar influence in a marked degree.

Glacial varves—Baron Gerard de Geer, of Sweden (1910, etc., 1926, 1927), has invented a method of measuring time by the annual clay layers, or varves, deposited under water during the retreat of the glaciers on the Scandinavian Peninsula and elsewhere. The process is given a firm scientific basis by a system of cross-identification of layers in different localities, similar to the cross-identification of tree-rings used in the present work. By this means he is able to enumerate several series of years, totaling some 18,000 since the glacial period. Measurements are made of the thickness of the layers, and thus evidence is found of temperature variations over long periods. The absolute date of these clay layers is known only within several hundred years. Dr. E. Antevs has applied the process in the valleys of the Connecticut and Hudson Rivers and at other points, finding some 4,000 years in the retreat of the glacial ice up the Connecticut Valley. These long sequences of annual layers displaying a temperature effect will be of greatest value in studying past climates.

Antevs's big-tree tests—Dr. Antevs (1925[3]) has made certain trials of the sequoias with reference to their use in studying past climates and reached an indecisive conclusion. But this result was anticipated from his selection of material and method of procedure. He divided Huntington's trees into basin and ridge trees, standardized them, and averaged these two classes separately without correcting the dating, and then compared the two curves obtained. These curves agreed for something like the last thousand years and before that disagreed. The difficulty lies in Huntington's incorrect dates (and possibly climatic change affecting the two groups differently). Basin trees grow rapidly and can be counted easily and so contain few errors, while the ridge trees are slow-growing and contain most of the errors. Hence, in them the average error would be of the order of twice the average error found in his dating, which was ±35 years in the last 1900. In view of these details, given in previous publications (Douglass, 1919, 1922), it should hardly have been expected that undated basin and ridge curves would show satisfactory agreement. On the other hand, it should be remembered that carefully dated basin and ridge sequoias show perfect cross-identification and only differ in the larger and more complacent growth of the former due to moist soil, as described in publications referred to.

Ocean rotation effects—One indirect effect of solar causes has been studied by Dr. C. F. Brooks (1926), namely, the rotation of the Atlantic Ocean under the pushing effect of the normal winds in different latitudes. The ocean is a vast storehouse of heat, whose variations are thus borne to different shores. The circuit takes some 2 years, and thus could originate short cycles of that order of length. Similar motion exists in the Pacific Ocean with probably an increased time of circuit.

Closely associated with the study of this ocean movement is the work of McEwen (1918, etc.) and Helland-Hanson and Nanson (1920) and others.

Solar cycle and terrestrial seasons—If a solar cycle of 10.5 months should exert a precipitation effect on the earth, it would alter the distribution of rainfall in different seasons, say in the temperate zone, and produce a 7-year cycle. We shall see that a cycle of this length plays a part in Arizona tree-growth, but it seems more likely produced by corresponding changes in solar activity and not as suggested above. If this short solar cycle were double the length given, or 21 months, and if its effect did not interfere with the seasons but increased tree-growth in each year of its occurrence, then we would find rings alternately large and small, as has been extensively observed. This is referred to in Volume I, page 106. Extended search has been made for a 2-year period by taking successive annual differences in growth and reversing alternate signs, and plotting. Such curves have shown extensive 14-year cycles and half-sunspot cycles. However, on testing rainfall records for such period, the weight of evidence favors a broken or variable cycle of some 28 months (Douglass, 1915; Clough, 1924).

CYCLES IN TREE-GROWTH

CYCLE RELIABILITY

Definitions—The value of a record of the past is its service for the future, and prediction becomes possible as repetition is recognized. Repetition may come at irregular intervals, in which case it may be wholly accidental; or it may come at nearly equal intervals, in which case it constitutes a cycle; or it may come at exactly equal intervals, in which case it can be called a true period.

Short variations—In studying variations of weather and trees, the first characteristic observed is the great number of short variations. These are usually interpreted as accidental and without significance, for if any large number of annual values be drawn by lot and plotted, we shall find in the curve a maximum number of 2-year periods, a lesser number of 3-year periods, and so on in decreasing rate, all of which, of course, are accidental. So the weather at any one locality is full of small variations which it is useless to work on at the start. Such variations remind one of waves on water. We can picture a combination of land outline and winds which would produce an exceedingly complex wave system, but we could probably determine the origin of each. We do not get the same bird's-eye view in the distribution of weather and we have to class small variations as accidental in the sense that they are far too complex to disclose their origins at present. But while these variations are now of no value in weather prediction, their existence does not prevent the existence of certain short-period variations buried in them which are not accidental and whose origins are worth tracing.

Long variations—Accidental and illusive periods decrease in probability as the length of the period under test increases. Many accidental 2-year and 3-year periods have been found, and even one 11-year period in numbers drawn by lot, but 20-year periods or over have proved extremely rare in accidental sequences. Therefore, in the analyses which follow, periods under 10 years have been given little weight unless extraordinarily prominent, and as the length of period advanced from 10 to 20 years and beyond, more and more reliability has been credited to any evidence of periodic variation.

Criterion of reliability—A criterion for judging the reliability of cycles has been suggested which for simple reasons has not yet received extensive use. It is applied by taking all the values in a curve containing the cycle, and twice drawing them out by lot; thus producing three curves, of which one is genuine and two spurious. If the genuine one can be distinguished from the others by the cycles alone, without other marks of identity, then the cycles are there. We can hardly yet make application of this to rainfall or tree-growth curves, because we do not know (or are just learning) what cycles ought to be there. On this account a half dozen criterion tests have resolved themselves largely into solving the question of the existence of cycles over 20 years, for that was the only known mark of identity. That in turn depended vitally on the length of the curve under test, for a cycle does not carry conviction unless it is repeated five or ten times in the record. So the trials on short curves of 50 or 75 years were not successful, while those on curves of 200 years were. It is probable that there will be extended use for this criterion, but in the absence of better knowledge of the cycles to be expected it has not been thoroughly tried and another method of judging reliability has been applied, namely, identifying similar cycles in many trees and over wide areas.

Cycle identification in small areas—In the early use of the cyclograph it became a matter of interest to know whether cross-identification could be done by cycles. To test this, an early general curve of the Flagstaff region was prepared as a standard. An assistant selected 125-year portions of other Flagstaff trees without letting me know to what tree or to what part of the 500 years they belonged. By cycles alone each unknown was compared with the standard 500-year curve. In the first trial of 10 unknowns, 7 were dated correctly, and in the next trial of 10, 8 were dated correctly. In other words, the cycles in any given tree in the region specified bear 75 per cent resemblance to a good average cyclogram of that region. Dating by size of individual rings is considered to have a reliability of 95 per cent or more. This decreased reliance in cycles is due in part to overimportance given in those tests to short-period cycles, before their unreliability was recognized.

Cycle identification at 200 miles—Two groups of 8 or 10 trees each, one from 40 miles north of Aztec, New Mexico (BMH), and the other from 18 miles east (AE), were compared with the Flagstaff records. The resemblance in the cycles is extremely close. Periods of 14, 17, and 21 years appear in all three groups in practically identical form. In this comparison cross-identification by cycles was carried over 225 miles of country (see Fig. 19 and Plate 9, page 132).

Cycle identification between Arizona and California—A still more difficult test was made between the Flagstaff area and the big-tree area. A selection of California trees was made in the following manner: The last 500 years of each of 34 trees were plotted and the resemblance of the cycles to Arizona and New Mexico cycles was reviewed and each tree marked in some way to represent its resemblance. The best four (D–4, 16, 20, and 21) were then taken by themselves, having a regard both to this resemblance and to their wide distribution in California, and the average record of the 4 trees plotted for 2,000 years. These plots were slightly smoothed and duplicated so that each one overlapped its neighbor half-way, and nearly every part of each tree's record appeared twice. In exactly the same manner two other complete sequoia records were prepared; one was an average of D–3, 12, 20, and 23, preferred for showing the sunspot cycle, and the second was the "best selected" sequoias, with good consistent records. All these were prepared by an assistant and marked by him with a reference letter, so that I had no idea of the date or identity of any curve. The assistant then selected 250 years of Flagstaff tree-records whose exact dating was also unknown to me. Comparison was made by cycles between the Flagstaff record and the unknown sequoia records. After they were completed, all dates of resemblance were looked up, and it proved that instead of the six possible correct coincidences, there were a dozen apparent agreements, of which six, or 50 per cent, were correct and the other six scattering. Thus it appeared that in group averages there is a 50 per cent resemblance between the cycles in tree-growth in Arizona and those in tree-growth in California, and that a fair assurance in cross-dating between these two regions can be reached, if one uses, as in this method, enough data from which to obtain a convergence of results.

Advantages of the cyclograph—This instrument, which converts mathematical integration into a photometric process, has been used almost exclusively in the analyses about to be described. Its extraordinary advantage is its rapidity of analysis and its flexibility in showing the analysis of every part of the curve at the same time in the cyclogram or differential pattern, and also in its independence of fixed periods, for it shows many periods at once, whether fixed, variable, or broken.

Disadvantages of the cyclograph—The chief disadvantage is that in its present form one can not assign quantitative amplitudes. This could be done by passing the photographic negative of the cyclogram under a recording photometer, of which there are several types sufficiently accurate. The amplitudes could be derived easily from the galvanometer curve.

PERIODOCRITE

Professor C. F. Marvin, chief of the United States Weather Bureau, has suggested (1921) the use of a process which he names the periodocrite. It simply solves the question: does the application of a given cycle reduce the probable error? If so, the use of the cycle is justified.

ZONE CENTERS AND THEIR MEAN CURVES

The material collected over western areas has opened such a field for immediate development that the contents of this chapter can only be regarded as a transition rather than a conclusion. Such progress and results as have appeared to date will be given, but they must be taken as subject to revision at a later time.

Cross-identification—Introductory to the comparison of smoothed curves, it should be recalled that cross-identification by individual rings is the exact and reliable method of comparing curves over large or small areas. In the western States it is found to grow easier and more reliable as the climatic stress of the arid regions is approached, that is to say, such dating is highly satisfactory within the Arizona region, which extends to the Rio Grande on the east and the coastline on the west. It is fairly satisfactory between Arizona and Central California, as also from Arizona to the central Rockies, but the northern States, with a very different tree-record, do not cross-date with Arizona. An electrical instrument is now under construction which it is hoped will reduce this cross-dating by individual rings to mechanical quantitative measurement. When that is accomplished it will perhaps be possible to express similarity between groups by a single coefficient.

Comparison of smoothed curves—The crests of these curves give the phase or epoch of maximum of the various cycles which may not be the same in different regions. Two results appear in this curve comparison, namely, first, a real separation into the three zones, and second, a latitude effect in which there is much more similarity east and west between the zones in their southerly or drier parts, than in the northerly moist latitudes.

Flagstaff area mean curve—In consequence of the southern similarity just mentioned, the Arizona area could be regarded as exceeding the others in size, for Pine Valley and Charleston Mountains show similarity on the west, and Basin Mountain, Aztec East, and Santa Fe repeat Arizona features on the east. However, the Catalina and Santa Rita Mountain groups near Tucson show marked differences. The Flagstaff area presents an excellent central homogeneous collection of curves from the Grand Canyon to the Rim and Cibecue, a distance of 175 miles (GC, FV, SH, NE, FL, FLU, RL, and J). These curves have been combined together graphically and the mean result, 1702 to 1920, is shown in figure 18, upper curve, page 128. This curve is important, because it is probably a better rainfall curve than those of the other zones. We note that shorter periods are largely smoothed out, except parts of a 7-year cycle. A period of 21 years (with lesser 14-year effects) strongly dominates, thus agreeing with a result reached in 1908 and referred to in the previous volume (p. 104). The sunspot cycle with its half and double appear in the early parts of the curve, as also 8.5 and 17 year cycles. Further discussion will be found below under Solar Records in Tree-Growth, page 125.

Pike's Peak area mean curve—The groups in the Rocky Mountain zone cover a smaller area than those in the other zones. Thus the area represented by the mean curve is limited to the east slopes of Pike's Peak in the vicinity of the Cog Railroad. The homogeneous collection of groups includes six, PPB, HNT, LNT, C, ST, and BDF. The Laramie group and those from Santa Fe and the Aztec region are similar, but not quite enough like the central collection to be included. The mean curve of the six named is shown in figure 13. It appears to show strongly a 5, 10, 20 year cycle and a triple sunspot cycle divided into halves and quarters (that is, an 8, 17, 34 year cycle).

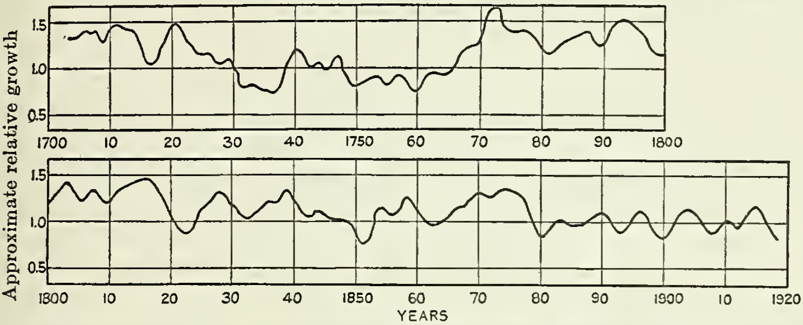

FIG. 13—Pike's Peak area mean curve, PPM; average of six groups, standardized and smoothed

Sierra Nevada mean curve—The distribution of groups in this zone is better than in the other zones. From The Dalles in northern Oregon to Pine Valley near San Diego the nine locations are fairly well spaced. There is pronounced similarity in the smoothed curves in all of these except Klamath Falls and Pine Valley, but the best agreement occurs between those in the Sierra Nevada Mountains from Calaveras to Mount Wilson and the mean curve is the average of these, namely, CVP, BC, EP, and W groups. It is given in figure 14.

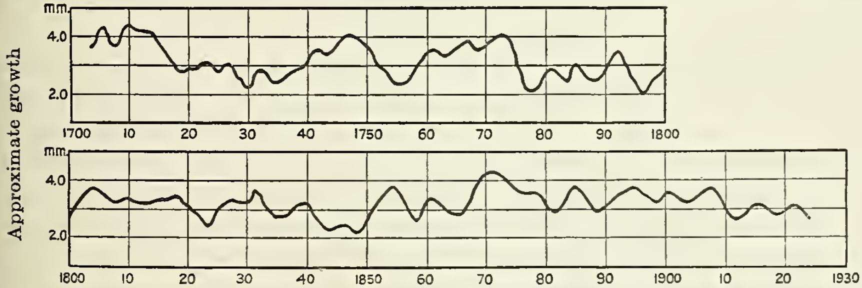

FIG. 14—Sierra Nevada area mean curve, SNM; average of four groups, standardized and smoothed

It will be noted that this inner group does not include the trees from San Bernardino Mountain, which show a remarkable double sunspot cycle. These were not included because they seemed to represent an extreme condition of some sort which should be studied by itself. A preliminary analysis of the Sierra Nevada mean curve shows a 5, 10, 20 year cycle, very strong in early half (1700–1800), a 5.8, 11.8, 22.8 year cycle, strong in the late half (after 1800), and a 7 ±, 14-year cycle growing strong in the late half.

METEOROLOGICAL AREAS: THE PROBLEM OF COMBINATION

Use of trees in outlining meteorological areas—Very few weather records reach 100 years in length, and they are apt to be at widely scattered places, subject to different conditions, such that the records can not be combined advantageously, but a forest gives a vast number of long records in some definite region. With proper care we do not need to mix records of different types. No doubt we have exaggerations, and in young trees we have a smoothing-down of variations. In terms of thermometer and measuring-rule, our values are not of the highest precision, but as seen from the viewpoint of actual growing vegetation the tree record is hard to surpass.

Disadvantages—While we have as yet no substitute for the length of record given by the trees, the chief difficulty is that the reaction of trees to certain weather elements that physical conditions make it easy for us to measure (temperature, precipitation, etc.) is not everywhere proportionate to these causes and under certain conditions may be fundamentally changed, as, for example, in the reaction to moisture in wet climates. The differences between the zones as shown below is perhaps in part an illustration of this. That investigation is as yet unfinished.

Problem of combination—Meteorological reports are collected in various districts which are political subdivisions, and are not outlined by weather conditions. When the student begins to combine areas in order to get general averages, he is confronted at once by the problem of combination, for before combining he has to find out what areas it is safe to combine without losing valuable material. The error of too large combination kept meteorologists from admitting solar effects in weather for a score of years.

Tree-record combinations—In work with the western groups the general experience has been that trees in the same forest are very much alike and may be combined without loss, if care is taken to use trees exposed to similar conditions of soil-moisture. Thus the groups were formed. In combining groups the guides have been: (1) geographical outlines of zones, (2) obvious similarity in smoothed curves which probably is equivalent to phase similarity in cycles, and (3) obvious similarity in cycle-length. The relations between phase and zone have been described above in connection with smoothed curves. The relations between cycle-length and zone are now under consideration.

Effect of combination on cycles—In a previous chapter the cycle analysis of each group was given, some 42 groups. Here we have a large number of widely scattered small units. The dominance of certain cycles in these zones seems very significant. When we combine the curves and use the mean curve for a homogeneous area, the cycles in this general curve are reduced in number, giving a few powerful ones and only traces of others.

Present importance of small units—It is felt that the group is still the important unit for analysis, and though more general combinations are illuminating and helpful, the fundamental information is in the group.

CYCLES IN WESTERN ZONES

Arcigram—In a periodogram the ordinates give the amplitudes of the various periods in a given curve. In the summaries below the ordinates give the number of occurrences of each cycle-length over a given area, and for the present the word "arcigram" is used to refer to this kind of a diagram. The distribution of cycle-lengths in the three western zones is shown in figure 15.

Derivation of ordinates—The number of groups in the three zones is nearly the same: Arizona, 14; Rockies, 15; Coast, 13. In the first plotting of figure 15, the ordinates consisted of the number of occurrences of cycles in each half unit of period; for example, those between 12.0 and 12.4 inclusive, and those within 12.5 and 12.9. But in the original analyses three weights had been assigned, and in the curves in figure 15 each occurrence is counted one, two, or three times as it was assigned weight. This inclusion of weights made no essential change in the curves.

Western area cycles—The cycle occurrences in the three zones were counted and plotted separately, and the important characteristic appeared that the cycles are much the same in each, with somewhat different emphasis. This similarity, as shown in the figure, is evidence in favor of the approximate values here given, which appear to be very nearly simple fractions of 34 or 35 years, as can be seen in the following list:

6.8	$\frac{1}{5}$	17.2	$\frac{1}{2}$
7.6 (rare)	$\frac{3}{14}$ or $\frac{2}{9}$	20.5±1	$\frac{4}{7}$ or $\frac{8}{5}$
8.6	$\frac{1}{4}$	22.5 to 24.0	$\frac{2}{3}$
10.2	$\frac{2}{7}$	25 + (rare)	$\frac{5}{7}$
11.2 to 11.7	$\frac{1}{3}$	28±1	$\frac{4}{5}$
14.2	$\frac{2}{5}$	31± (rare)	$\frac{6}{7}$
		35±	1

This relationship of western cycles only appeared in recent work and is still provisional. It may be real, but, on the other hand, there may be some preferential selection by the analyzing instrument or the observer, in spite of great effort to get rid of such errors. It should be added that the cycle given as 20.5±1, really covers the interval from 19 to 21, and could have interpretations at 19, 20, or 21 years. The brief study, given later, of solar records in the long Flagstaff tree-records, throws a little more light on this.*

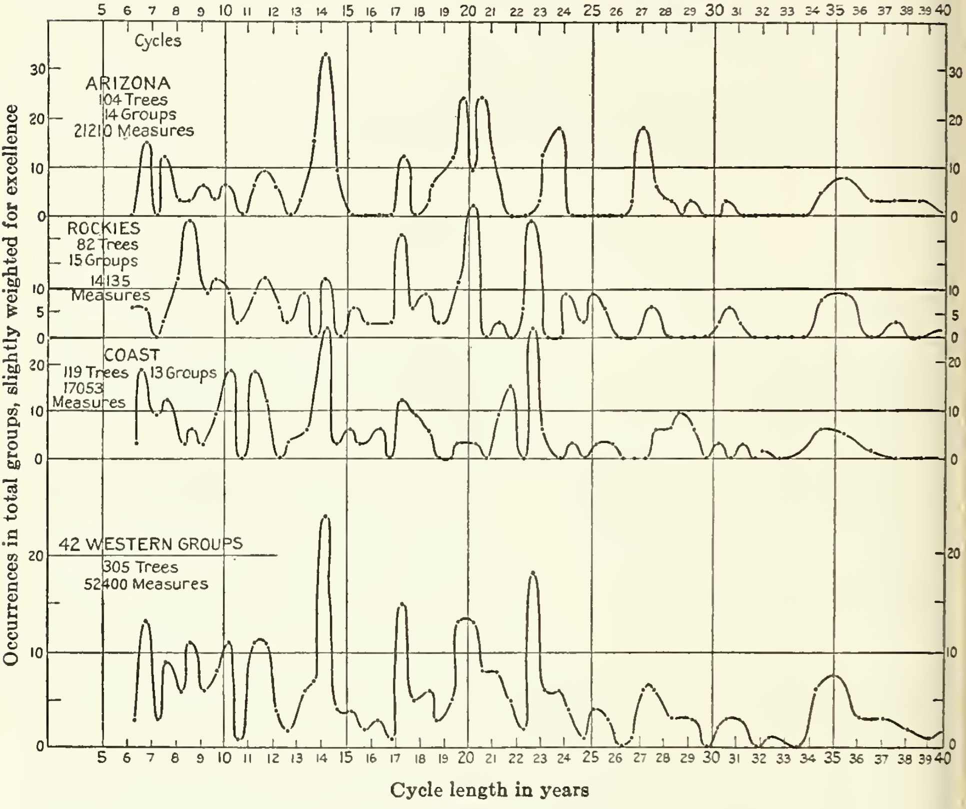

Fig. 15—Cycles in western zones

Arizona zone—The Arizona zone is distinguished by the absence of 8, 10, 11, and 17 year cycles and the great dominance of 14 and 20 years. Its double sunspot cycle averages a little over 23 years.

Rocky Mountain zone—Cycles of 10, 11, and 14 years are largely lacking. The 8+ and 17 year cycles have more prominence here than in the other zones, but the 20 and 23 year cycles are the strongest in the zone.

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*Recent independent tests sustain these results.

Coast zone—Cycles 17 and 20 years are largely lacking. The 10 and 11 year cycles are stronger here than in the other zones, but the 23-year cycle is the strongest in this zone.

Zone summary—The characteristics of the three zones are brought out in the following list:

Zone	Prominent	Deficient
Arizona..............	14 20 years	10 11 17 years
Rockies.............	8 17 20 23	10 11 14
Coast................	10 11 14 23	17 20

Sequoia cycles—The above summary deals almost entirely with the yellow pine; for comparison the cycle analyses of some 32 sequoias, from 1400 on, have been combined into one arcigram which agrees with the pines in the coast zone in giving prominence to cycles of 10, 11, and 14 years, but differs from them in having a very prominent 20-year cycle with lowered emphasis on the 23-year cycle. This includes the entire list of sequoias in the General Grant Park region without selection of any kind, and indicates more resemblance to the Arizona reaction than appears in the pines of the same area.

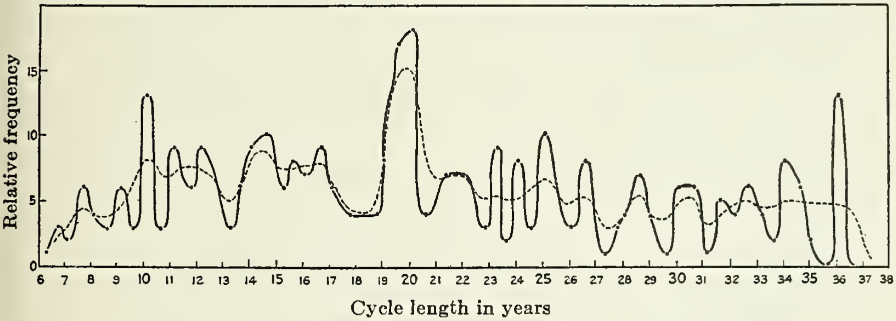


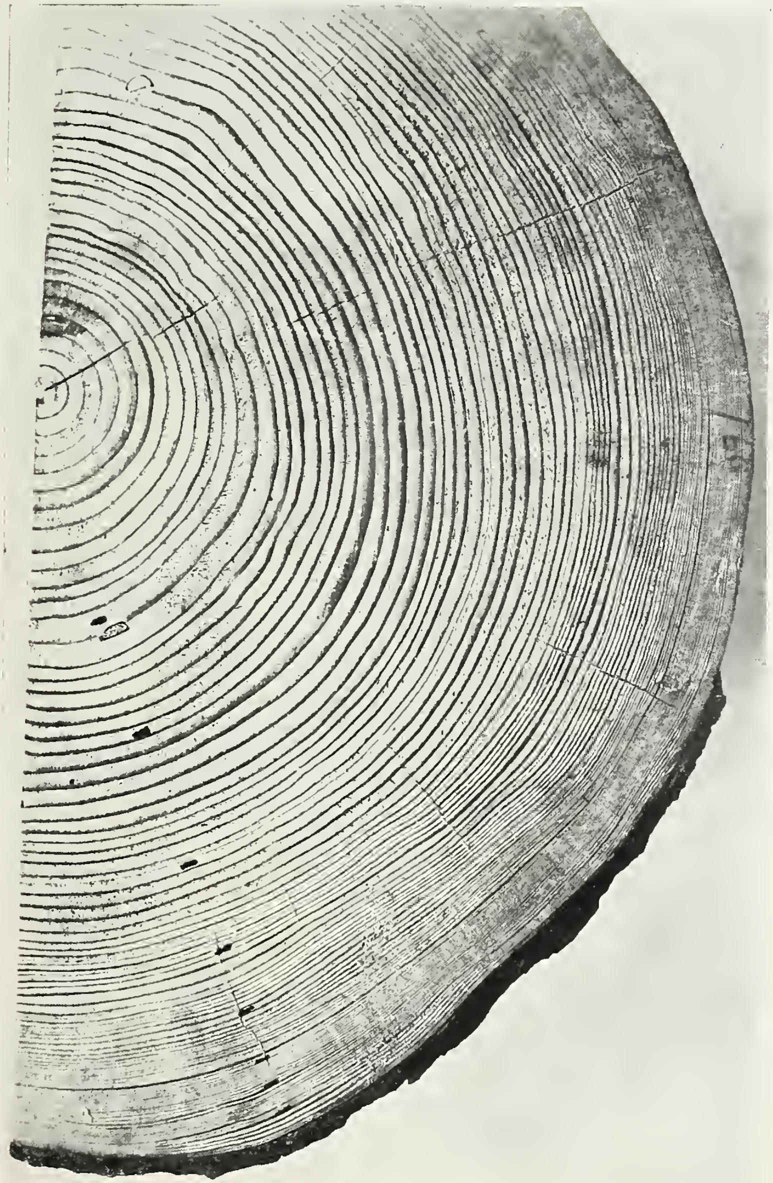
FIG. 16—Sequoia cycles

SOLAR RECORDS IN TREE-GROWTH

Historical confirmation—From the start the sunspot cycle was sought in the Arizona pines, and during large portions of their growth it seemed perfectly evident, but for scores of years near 1700 it failed entirely; in 1914 the writer very nearly gave up the idea that the trees show it. In 1919 (Volume I, p. 102) the cycle record was given with the statement that from 1660 to 1720 the sunspot curve "flattens out in a striking manner," and again, "the sequoias show strikingly the flattening of the curve from 1670 or 1680 to 1727," and again, "it seems likely that the sunspot cycle has been operating since 1400 A. D., with some possible interference for a considerable interval about the end of the seventeenth century." Early in 1922 a letter was received from Professor E. W. Maunder, of England, calling attention to the prolonged dearth of sunspots between 1645 and 1715, and saying that if there were a connection between solar activity and the weather and tree-growth, this extended minimum should show in the weather and in the trees. On receipt of the letter, this period was immediately recognized as the interval referred to in which there was entire failure in attempting to trace effects of the well-known solar cycle. The sequoia record for the last 500 years, as summarized in figure 33, page 103, of the previous volume, confirms minutely the result. So also do the Vermont hemlocks and other tree-records.

Dearth cycles—In 1922 or before it was noticed that when the 11-year cycle disappeared from the trees near 1700, two other cycles, one of 10 or 20 years and the other of 7 or its smaller multiples, became prominent in its place in the Arizona pines (see Plate 9 and Fig. 19). Soon after, it was noticed that the Vermont hemlocks and the sequoias of California show similar change at that time. And then it was observed that these three cycles appear generally in the western trees; they are, first, the known sunspot cycle of about 11½ and its double of 23 years; second, 10 or 20 years; and, third, 7, 14, 21, or 28 years. These three cycles, with others mentioned below, have been confirmed in the present study of the 42 western groups. There is some reason to think that all of these cycles come from the sun, for at different times the sunspot cycle itself has changed to one or the other of them. For example, from 1748 to 1788 there were four complete cycles of close to 10 years each; and from 1788 to 1837, 49 years, there were three complete cycles of about 14 years each and one of 7. It seems at least likely that these other two cycles, found in western trees with extraordinary persistence, are also of solar origin.

Wet and dry climatic effects—In this study of cycles in the western yellow pine it was found that in this dry region, where trees are specially sensitive to rainfall, they show, besides other cycles, a double-crested 11-year variation, just as the rainfall itself does, but in the moist coastal regions this solar cycle has more often a single crest like that of the sunspot numbers. This agrees with the result of 10 years ago, in which the wet-climate Scotch pines of North Europe, especially near the Baltic Sea, showed a direct single-crested cycle having a remarkable resemblance to the curve of sunspot numbers (Volume I, p. 77). Their growth gave the solar changes with an accuracy exceeding that of any trees of the southwestern area. (See S–14 in Plate 9.) This remarkable solar record is a wet-climate phenomenon, but it is not yet clear just what causes its accuracy. It seems probable that these trees follow the sunspot cycle more



Spruce, S-14, from South Sweden, showing sunspot cycle; wet climate reaction. Dots give dates of sunspot maxima beginning with 1830

closely than do the weather elements in which they live, and it is perhaps safe to repeat the suggestion made by the writer in 1922 that there may be some more direct line of cause and effect from the sun to these trees than we have taken into account, such, for example, as radiation (possibly of short wave-length), that is especially favorable to trees growing generally under cloudy skies. In tree-groups along the Atlantic coast of this continent, the 11-year cycle is also prominent, but it has a phase displacement of 2 or 3 years.

SOLAR CYCLES

Eleven-year cycle in long Flagstaff record—Combining the long Flagstaff century curve beginning in 1285 with the Flagstaff mean

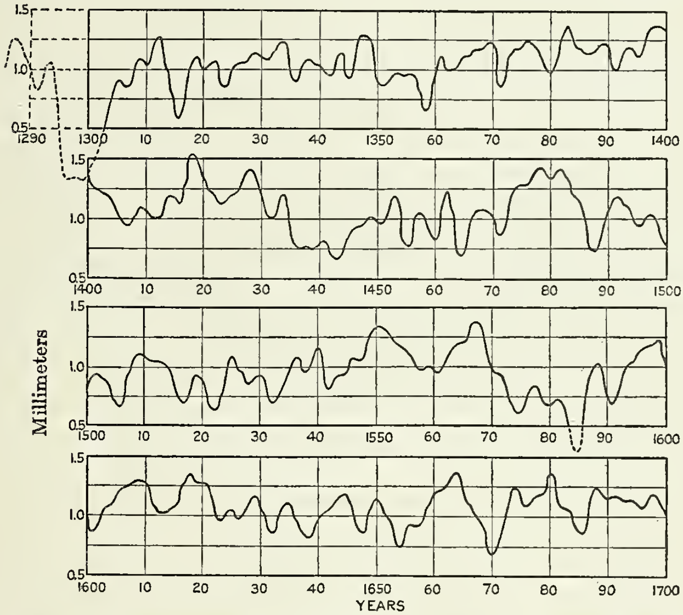


FIG. 17—Flagstaff century curve, FLC, A.D. 1285–1700; standardized and smoothed

area curve from 1700 on, one has full 625 years of sensitive tree-growth (see Figs. 17 and 18). To this a superficial graphic analysis has been applied with a number of interesting provisional results. The first test deals with the extended half-sunspot cycle in the early Flagstaff curve, found in 1908 and shown on page 102 of the previous volume. The first hundred years of our present curve is made up of several radials of one tree which had suffered a considerable injury in 1295. It begins to show the cycle with certainty about 1320. The cycle continues without interruption till 9 other trees join it between 1385 and 1419, during which time it is discordant, probably in part from poor merging process in adding the new trees. Then it continues without discord till 1541, 1550, and 1566–67. After that it is in accord again till 1617, and from there on it decreases its accuracy, and the variations typical up to that point disappear from the curve. The curve from 1700 on shows much less of the sunspot variations, but in the Grand Canyon group, one of its components, and others also, the half cycle shows well from 1850 to the time of collecting and with almost the early regularity. Brief calculations show that the long variation in the earlier curve agrees exactly in phase with the recent years, and so we find through practically 600 years a mean value of the sunspot cycle of 11.30 ± 0.02 years. From the correlation diagram already referred to on page 104 of Volume I, we see that the most direct relation between the double-crested growth-curve of the above stated length and the single-crested sunspot curve is that a growth maximum occurs at the time of a sunspot minimum. On

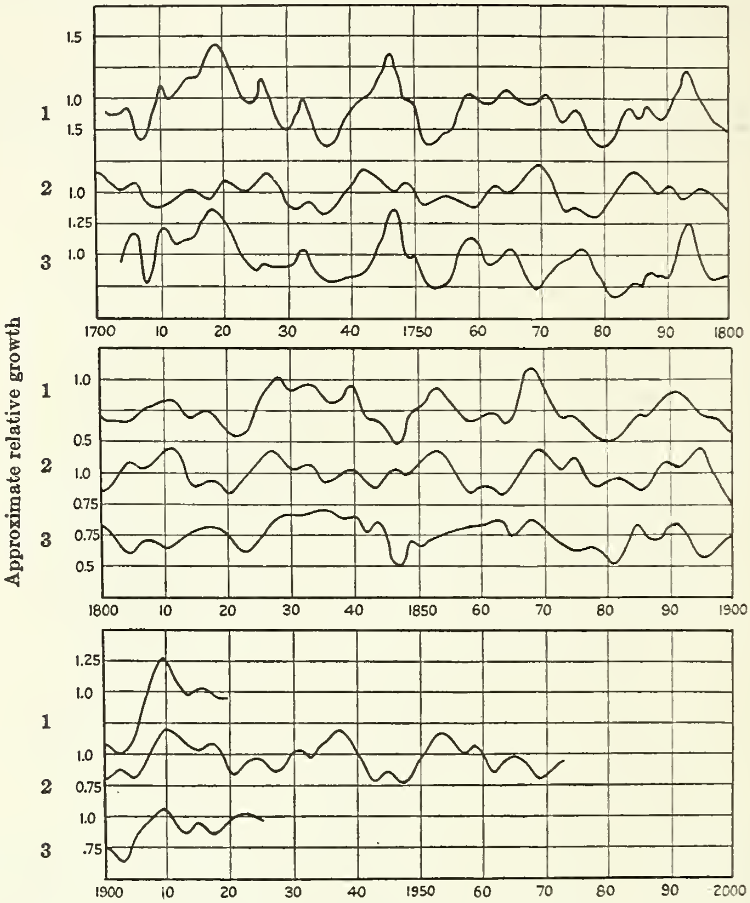


FIG. 18—(1) Flagstaff area mean curve, FAM; average of eight groups, standardized and smoothed; (2) synthetic curve; (3) residuals

plotting in the early times of sunspot maxima and minima, according to Wolfer, we find that the telescope was invented and spots observed just in time to show that it has always been the same maximum of the double-crested tree-cycle that came at sunspot minimum. This in itself is an interesting fact, for it intimates that the 11-year cycle can be called a well-defined period which the sunspots do not always follow exactly. Apparently, the 11.30-year period and the sunspot cycle are two different things.

Seven years and multiples—There is further information in the tree-records which perhaps adds light but does not fully solve the solar puzzle. The Flagstaff area mean curve in figure 18 has some large variations which are roughly solved without difficulty. A 21-year cycle is very prominent and a 14-year and a 7-year cycle easily evident. These values seem to be very close to 7.0 and its multiples. The time of maximum of the shorter periods is about 1910 and for the 21-year period possibly 4 years later. This, however, is not a rigorous solution. The amplitudes (from the mean value) increase from 5 or 10 per cent in the 7-year to double that in the 14-year and triple in the 21-year periods. This group of multiples of 7.0 becomes evident about 1663 with a large maximum of the 21-year type. It rather fails in the 1680's, but after 1700 comes in regularly. Its beginning is thus connected with the great dearth of sunspots described by Maunder (1922). A single maximum of this apparent type occurred in 1479.

Nine-year-plus cycle—A very crude graphic synthesis of these periods has been made (and extended to 1980) whose resemblance to the original curve is fair. This is shown in the central curve in figure 18. So a set of residuals between it and the original was plotted and two interesting features appeared, as shown in the third curve of Figure 18. A set of crests came in 1747, 1758, 1766, 1777, 1786, and 1794, all of which except the last came close to the sunspot minima during that unique interval when the sunspot cycle averaged about 9.3 years in length. (The minima were 1755, 1766, 1776, 1784, 1797.) The length derived from these crests is 9.4 years, which thus gives us a terrestrial cycle related immediately to a definite solar cycle. It is possible that the fairly common climatic cycle of 19 years is the double of this solar cycle. From 1800 to 1880 the agreement between the natural and synthetic curves is good, except for the extreme minimum growth in 1847 and 1880, 33 years apart, and from 1880 to 1905 the 7-year cycle is practically absent, reappearing again subsequently.

Historical changes—In a general way it is safe to say that the sunspot cycle and its double and triple values are very common. The double value has persisted in Arizona for 600 years with interruption from 1630 to 1850 or thereabout, and in some North European localities it shows for the last century and a half covered by our tree groups.

The triple period, essentially Brückner's cycle, has operated in Arizona for the last 200 years and in Norway for 400 at least. Western zone cycles are largely its simple fractions. A hundred-year cycle is prominent throughout the 3,000 years of sequoia record, and a cycle of about 150 years shows in the 600 years of yellow pine. It seems fairly probable that the 11-year cycle can be judged by the variations in its double value, which in some cases is more easily traced through long periods. A very incomplete review of the sequoia record suggests that from 1300 B. C. to well after 1100 B. C., the 11-year cycle was strongly developed. Near 300 B. C. it was again apparent, though not very conspicuous. During the first two centuries of our era it was again highly dominant. It reappeared from 375 to 475 and from 600 to 650 and was operating during much of the ninth century, though mixed with other cycles. Then it appears only occasionally until after 1300, when it again becomes fairly continuous, except for the changes in the seventeenth century (1633 to 1712) above noted. This is a provisional report and will, without doubt, receive changes when the sequoia records are minutely examined for the purpose.

Climatic patterns—From this study of the geographical and historical distribution of climatic cycles it is inferred that they are climatic patterns made up of interferences between a number of simple fractions of a few fundamentals, traceable to solar influence. This form of interference seems to produce pseudo-cycles which vary with the phase relationship of the fundamentals and whose resulting temporary character has always been a stumbling-block in the way of investigation.

CYCLOGRAMS

An analytical review of some of the cycles mentioned in this chapter is given in Plate 9. To one who understands the extent of information in the cyclogram, and, if I may add, the spirit of this information, that is, its frankness in showing its own accuracy or error, these figures visualize the facts in a most compact and convenient way.

Cycle identity across 200 miles—The first three cyclograms, taken in immediate succession on the same plate, show an analysis at a period of 18.1 years (represented by the thread) of the Flagstaff curve and the two points near Aztec in northwest New Mexico, from 1700 to about 1910. The most conspicuous alignment is the 21-year cycle, but 17- and 14-year cycles also usually show. The similarity in general pattern is apparent at once. This is evidence of the reality of the cycles and of their climatic significance (page 118).

Dearth cycles at A. D. 1700—The Vermont hemlocks give an analysis shown in cyclogram 4. Here the Brückner cycle dominates from

1650 for more than 100 years, accompanied by a 28-year cycle, of which traces are found to continue even in the late half (1775 to 1900), in which the sunspot cycle and its double prevail. The latter condition extends from about 1750 to the present time. In the early half also a 20-year cycle is faintly shown by a distinct alignment, as marked in the explanation diagram. So in this record also we find the 11-year cycle replaced by 20- and 28-year cycles during the dearth of sunspots near 1700 and for a brief time after, that is, to about 1750.

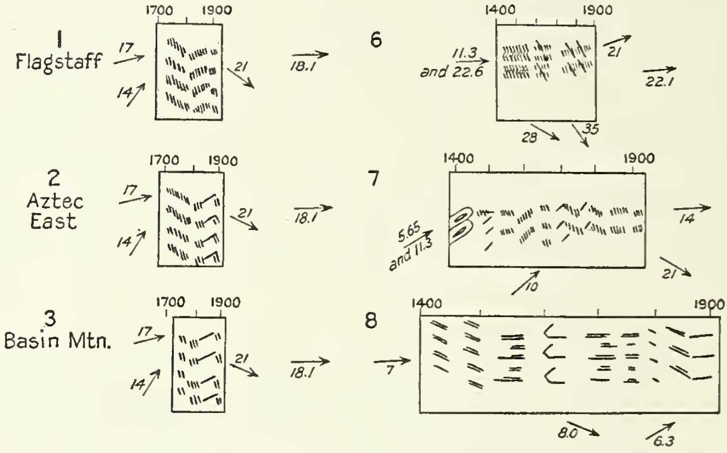
Cyclogram No. 5 gives an analysis of the sequoia record in four trees, D–3, 12, 20, 23, which were selected for their excellence in showing the solar cycle. The interval covered is the 400 years from 1450 to 1850 at a set period of 23 years, represented by the thread. The change from the double sunspot cycle to the 10, 20-year cycle took place near 1630. At about 1700 all three cycles (10, 20, 23, and 28) begin to show. In the last half century or so, the 20-year cycle dominates, which agrees with the "arcigram" of the sequoias mentioned a few pages above. The dearth cycles (20 and 28) were forming by 1550 more or less, and they are the ones which prevail during the absence of sunspots near 1700.

The Flagstaff evidence of dearth cycles is shown in cyclogram 6. Here it is easy to trace the double sunspot cycle from 1400 to its end near the center at 1650. The 14, 28-year cycle enters at about 1550, but after 1700 it is practically lost, due to smoothing and the great dominance of the 21-year variation, which continues to the end. The 35-year variant begins not far from 1700. This cyclogram was taken in 1921 from the original Flagstaff group, smoothed by 5-year overlapping means; all the others shown are from original unsmoothed plots or from Hanned curves.

Flagstaff long record—Cyclograms 6, 7, and 8 show the analysis of the long Flagstaff record (500 years used here) at three different settings for cycle-length, 22.1, 14.0, and 7.0 years. The first, as just described, shows the main features of the sunspot cycle to 1650 and the 21-year cycle since 1700. The second gives more detail. The 14-year cycle enters near 1500 and continues to the end. The 11-year period, often double, may be traced from 1400 to well after 1600. A 9- to 10-year cycle is evident from about 1650 to 1775 or so. Thus the "extra" cycles (10 and 14) are clearly found connected with the dearth of sunspots about 1700.

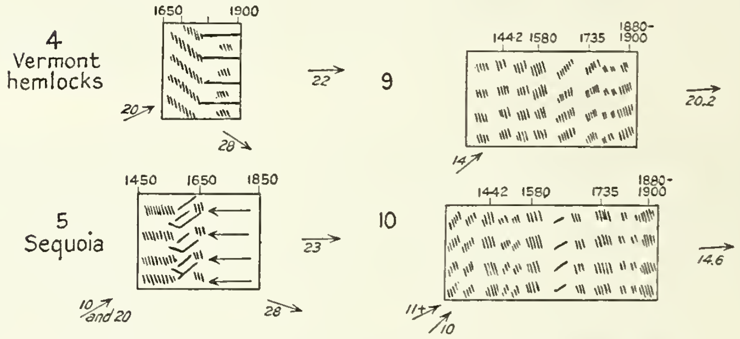
The Flagstaff analysis at 7.0 years is given in cyclogram 8, but the numerous short cycles shown are not so important and sure as the longer ones already described.

Arizona drought cycles—There is no doubt that a demonstration of the periodic action of droughts would be of great value to the Southwest. Accordingly, in 1925 a "skeleton" plot of Arizona droughts, shown in the trees, was made and analyzed. The major dry periods came at 1440, 1580, 1735, and 1880 to 1900, or an average of about 150 years apart. Also, the single tree which gives a record beginning at 1285 shows a great depression at 1295 to 1300, which conforms to this 150-year spacing. Thus the major droughts give a cycle which was long since (1914) noted as occurring in the Arizona record. Cyclograms 9 and 10 show analyses at 14.6 and 20.2 years as the best to cover this 575-year lapse of time. These cycles are near the 14.0 and 21.0 values and may be identical. It will be seen that there is a tendency to group the droughts at intervals of something under 50 years. This could be 42 years, the interval at which 14- and 21-year cycles have their major effect on each other. Probably the 150-year effect emphasizes whichever 21-year multiple is nearest, with some modification from the 14-year cycle.



Cycle identity across 200 miles

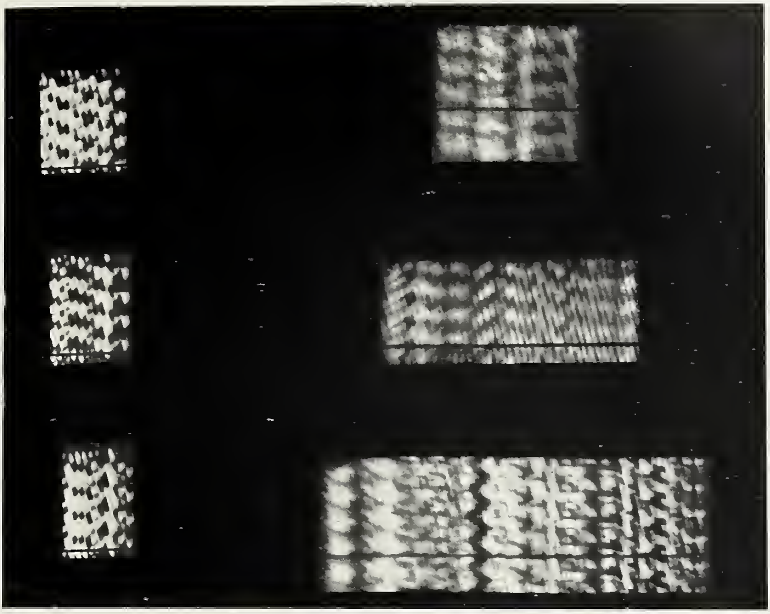
Flagstaff cycles near 7,14 and 22



Dearth cycles at 1700 A.D.

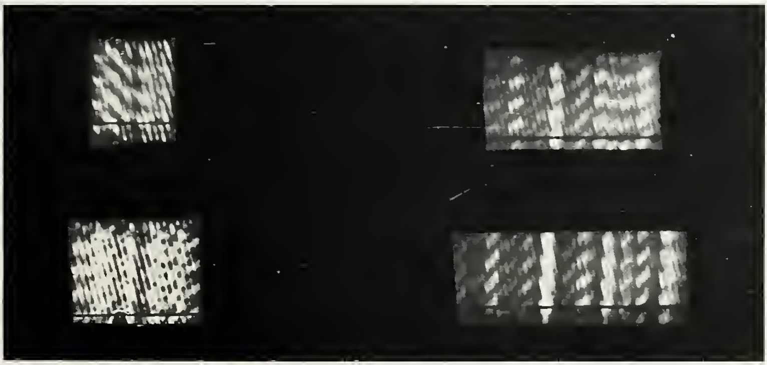
Arizona drouth cycles

FIG. 19—Details of cyclogram patterns in Plate 9



1, 2, 3—Identity across 200 miles

6, 7, 8—Analyses of Flagstaff pines



4, 5—Dearth cycles near 1700 A.D.

9, 10—Cycles in Arizona droughts

Cyclograms

Explanatory diagram on opposite page

CYCLES AND CLIMATE

Three major lines of interest have emerged in this study of cycles as it has developed in this chapter. The first was the distribution of cycles over western areas in approximate simple fractions of 35 years (or perhaps the triple sunspot value of 33.94 years); the second is the history of cycles in the long Flagstaff record and their agreement with solar changes, thus throwing light on solar history; the third now to be considered is the problem of prediction, which depends directly on the climatic significance of the cycles previously discussed. Their climatic character seems open to no reasonable doubt. Dating and prediction, the backward look and the forward look, both depend on a knowledge of the historic and geographical distribution of these cycles. In each it is better to test out a small locality first, such as the Flagstaff region, in order to avoid the complexities which arise over too large areas.

First caution: Interpretation differs with locality—The Arizona trees respond closely to a definite weather element, rainfall, the most important element in the prosperity of the country, but in the moist areas this direct response decreases and even disappears. Hence, the first caution in this process is that we must not assume relationships similar to those in Arizona in any given place until that place has been thoroughly investigated.

Second caution: Cycle changes not understood—The second caution is very important. Until we know the physical cause of cycles we can not say how long a mechanical repetition will last, for it may break down at any time. This is well illustrated in the solar changes shown in the long Flagstaff record. For hundreds of years the 11-year cycle was dominant, and then in the middle of the seventeenth century it faded out and gave place to others, and we do not yet know the reason. Until we know the reason we can not be sure it will not happen again in the near future. Fortunately, we have the long-lived sequoia for testing out secular changes. The best results from it at the present time were given in a historical summary above.

Variable star analogy—There are several variable stars which are dominated by different periods for irregular intervals of time. One of the best is SS Cygni, which has been observed carefully for more than 30 years. It is not visible to the naked eye, but by telescopic observation has been found to rise suddenly from the twelfth to the eighth magnitude at intervals of 50 or 60 days, more or less. Alternate maxima are often of different length, reminding us of alternate sunspot maxima. Then without warning the period changes. Dr. Leon Campbell, of Harvard College Observatory, has given me data and for years I have tried to find the rule which governs these changes.

Third caution: Cycle subdivisions—The splitting of cycles that may differ in different localities causes an uncertainty in place of maximum or minimum. Consider, for example, a yearly curve of temperature, low in winter and high in summer. Impress upon this, as we have in Arizona, a summer rainy season which lowers the daily averages and produces a slight summer minimum. The maximum is split and driven each way, but owing to the lag in effects the higher maximum comes in June. If a cycle is split we need to know whether it is the maximum or minimum that changes. If only one changes we get a double-crested curve and if both maximum and minimum split we get a three-crested curve. In the 120 or 130 analyses of western groups, certain cycles, obviously the same in each case, were sometimes found single, sometimes double, and very rarely triple. Hence, it is evident that the comparison of dates of maxima and minima is a complicated process.

Fourth caution: Interference cycles—If some tree cycles arise, as is possible, from an interference between some external short cycle, say 10.5 months, and the annual seasons, then it is evident that the time of maxima would not necessarily be the same in different geographical locations, for the time of favorable season is different. Comparison between the northern and southern hemispheres would be needed to settle such cases, for similar conditions in the two hemispheres would reverse the cycle. A single curve from Tasmania suggests a split 35-year cycle, with major maximum about 1891 and minor maximum in 1908. In the early Arizona curve the maximum of the 35-year cycle was put about 1900, but in the recent study of western groups this 35-year cycle is usually split into two 17-year cycles whose maxima come in 1892 and 1909, thus agreeing with Tasmania.

Fifth caution: Cycle centers—In the western zones it was found that each zone had a homogeneous central area with scattering variations about it and that intermediate points, such as the Charleston Mountains, partook of the variations of each zone near it. It is not impossible that we shall find several more central homogeneous areas from which certain typical effects spread out. It is evident that in such conditions many intermediate places will have badly mixed conditions, so that prediction of any kind will become additionally difficult.

Flagstaff area synthetic curve—The mean curve covering the area from the Grand Canyon to the Rim shows very excellent similarity to the individual curves composing it, but many of the short periods have disappeared and multiples of 7.0 years are left prominent, 21 years being by far the strongest. Residuals between the synthetic curve and the real growth-curve show a 9.4-year cycle in the latter part of the eighteenth century. Crests are too high (in the natural curve) at 1793 and 1891 and the minima at 1847 and perhaps 1880 are too low to be accounted for by the synthetic curve. The 7-year cycle was almost absent from 1880 to 1905. Yet on the whole there is a good deal of similarity. The prolongation of the synthetic curve shows a small depression near 1927 and deeper ones at 1942 and 1947. The interval during the 1930's has high ordinates with an unimportant depression at 1933. It is possible that the 1947 depression may resemble the one of 1847 and be rather extreme. During the 1950's the curve is again high. High crests occur at 1937 and 1953. It is not expected that this is entirely right, but the details are given here in order to assist ultimately in finding the true variations.

SUMMARY

The foregoing book includes the following descriptive matter:

1. The technique of collection and preparation of material brought up to the latest development, with special studies of trees and rings.

2. New instruments constructed and used, namely, the tubular borer, the automatic plotter, the longitudinal plotter, and the White cyclograph (periodograph without the attachment for producing the periodogram); the cyclogram is here definitely used in place of the periodogram.

3. The collection of long tree-records including (*a*) sequoia groups from Calaveras and Springville, (*b*) coast redwood groups from Santa Cruz and Scotia, (*c*) a 640-year yellow pine, and (*d*) much archæological material for constructing a very long yellow-pine growth record.

4. The collection and measurement of 305 yellow-pine ring records in 42 groups, from 10 western mountain states, representing the area from the eastern slope of the Rockies to the Pacific coast and extending from the Mexican border to the latitude of the Columbia River. Practically all these trees were standardized individually before obtaining group averages.

The results obtained and described are as follows:

1. All the sequoia groves from Calaveras to Springville give the same climatic record and can be cross-identified throughout their records; the northern groves are more complacent in ring-type.

2. The coast redwoods, carefully selected and most carefully compared, could not be cross-identified and therefore are not used.

3. Ten-inch boring tests every 20 feet on a sequoia 265 feet long and 15 feet in diameter, which fell in 1901, gave almost perfect similarity throughout in the heartwood, but very considerable differences in the water-soaked sapwood. The problem of change in ring-size is opened. In living trees the change is probably very small and connected with conservation of moisture, sometimes possibly retroactive on the rings.

4. Topographic studies show that soil moisture is a strongly controlling factor in ring-type, both in sequoia and yellow pine. Soil-moisture gradient below the trees could be used as an indicator of ring characters.

5. Trees at higher altitudes and at higher latitudes (than about 32° N.) show more complacent rings.

6. Close grouping in the pines and sequoias produces objectionable alterations in rings only under extreme conditions and can be avoided with trifling care in selection of trees.

7. Deficient soil-depths and denudation of soil about trees produce intensely compressed outer rings in the pines of dry areas, and this character can be recognized in much prehistoric material.

8. Mean sensitivity is a good indicator of climatic correlation, but it is strongly affected by injuries to the tree.

9. Average ring-size, doubling, changing, and other characters of rings can be used as indicators in judging the surroundings, and especially the climates, of prehistoric and geologic times.

10. The Prescott correlation between rainfall and tree-growth is continued and a similar correlation is found between the Flagstaff trees and the winter rainfall recorded there, which, in turn, closely resembles California precipitation. A close correlation is also found between carefully selected (dry ground) sequoias and San Francisco rainfall.

11. By comparison of smoothed curves, three western centers appear; Pike's Peak, Flagstaff, and Sierra Nevada. The Pike's Peak area as worked out covers the eastern slope of the mountain; the Flagstaff area extends from the Grand Canyon to the Rim and Cibecue, 175 miles; the Sierra Nevada area extends from the Calaveras Grove and even farther north to Mount Wilson and farther south, 500 miles. In each of these the curves of growth are homogeneous, and at points between these major centers, such as Charleston Mountain or Aztec, mixed effects are found.

12. Dating comparisons of cycles in 200-year curves show 75 per cent resemblance in local curves of individual trees, and 50 per cent resemblance between Arizona pines and California sequoias, by large groups of trees. Practical identity of cycles in yellow-pine groups is found across 200 miles between Flagstaff and northwest New Mexico.

13. The cycles found in the yellow pines of the western zones emphasize the approximate simple fractions of 34 or 35 years, with 11 and 14 years dominating on the coast, 14 and 21 years in Arizona, and 10 and 11 (or 23) in the Rockies; the coast is deficient in the 20-year variations (the separation of 19, 20, and 21 is not yet fully determined in these zones); Arizona has less of the 11, 23 year cycles and the Rockies are short in the 14, 28 year cycles; they, however, show the 8.6- and 17.5-year cycles better than the other zones.

14. A sequoia arcigram (cycle summary over an area) shows a little more of the Arizona character in the sequoias than in the yellow pines of that region.

15. The long Flagstaff record, from 1300 to 1925, perhaps the best in the three zones for rainfall history, gives cycles which check with the known solar record. From them we get a solar period of 11.30 years lasting for 600 years, but with an interruption from 1630 to 1850; we get also a group of 7, 14, and 21 year cycles beginning near 1660 and well established after 1700. The 21-year cycle has dominated Arizona tree-growth for 200 years. A 9.4-year cycle shows in the late 1700's, when the sunspot cycle was of that length. The 7-year cycle was less active from 1880 to 1905 (in the Flagstaff area mean curve). Growth maxima occur at observed sunspot minima.

16. Wet and dry climate effects in trees in relation to the solar cycle are confirmed.

17. Provisional results indicate that the 11-year cycle appears in the long sequoia records at 1300 to 1100 B. C., 300 B. C., A. D. 35 to 240; 375 to 475; 600 to 650; 800 to 900 and 1250 onward, with the interruption following 1700.

18. The dry years in the Flagstaff area tree-growth analyze best on 14- and 21-year cycles with major droughts at about 150-year intervals and minor droughts at 40- or 50-year intervals.

19. The extension of the cycles observed in the last 200 years in the Flagstaff area indicates possible large growth of trees in the 1930's and 1950's, with depressions in the early and late 1940's.

It is recognized that much of this work is new and that time is needed to test and improve it, but it is hoped that these preliminary results are not greatly in error.

APPENDIX

TABLES OF GROUP AVERAGES, STANDARDIZED

ARIZONA ZONE

FLAGSTAFF (FL), APPENDIX, VOLUME I, PAGE 113

Flagstaff University Section (FLU), 500-year trees

A.D.	0	1	2	3	4	5	6	7	8	9
1700	0.98	1.07	1.00	0.86	1.03	1.22	1.40	0.77	0.69	0.85
1710	1.01	0.79	0.85	0.85	1.05	1.08	1.17	1.08	1.20	1.03
1720	1.27	1.04	0.93	1.34	1.00	1.22	1.57	0.80	0.94	0.64
1730	1.04	0.84	0.95	0.85	0.90	0.51	0.84	0.76	1.14	0.76
1740	0.93	1.11	1.11	1.08	1.13	1.11	1.39	1.09	0.64	1.21
1750	0.91	0.75	0.45	0.69	0.61	0.72	0.65	0.83	1.15	0.98
1760	1.05	1.10	1.37	1.24	1.54	1.23	0.79	0.96	0.82	0.76
1770	0.95	1.12	0.88	0.67	0.85	0.97	0.88	0.97	0.60	0.60
1780	0.62	0.72	0.51	1.01	1.32	0.62	0.70	1.11	0.95	0.67
1790	0.90	0.86	0.99	1.21	1.20	0.92	0.90	0.98	0.79	0.95
1800	0.76	0.56	0.97	0.85	0.61	0.77	0.99	0.69	0.86	0.96
1810	0.98	1.18	1.09	0.49	0.94	0.86	0.80	0.67	0.60	0.85
1820	0.69	0.61	0.53	0.62	0.64	0.92	1.12	0.87	0.96	0.85
1830	0.96	0.82	0.98	1.02	0.70	0.80	0.80	0.80	0.76	0.92
1840	1.00	0.70	0.72	0.82	0.74	0.67	0.58	0.40	0.80	0.91
1850	1.00	0.77	1.13	1.29	1.09	1.02	1.06	0.84	1.11	0.88
1860	0.98	0.92	1.07	0.78	0.70	0.86	1.04	1.02	1.33	1.04
1870	1.14	0.84	0.94	0.82	1.05	1.06	0.72	0.70	0.85	0.75
1880	0.69	1.01	0.88	0.86	0.81	1.10	0.80	0.86	0.95	0.96
1890	1.12	1.12	0.98	1.36	1.21	1.05	1.34	1.18	1.26	0.95
1900	0.71	0.83	0.80	0.79	0.63	1.14	1.24	1.28	1.64	1.80
1910	1.68	1.66	1.42	1.19	1.42	1.36	1.36	1.00	0.95	....

Fort Valley (FV), 6 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1680	....	....	....	....	....	....	0.50	0.83	0.85	0.90
1690	0.86	0.82	0.90	1.06	0.85	0.76	0.89	1.43	1.30	1.61
1700	1.24	1.35	0.97	1.05	0.88	0.70	1.20	1.36	1.28	1.61
1710	1.91	1.56	1.54	1.71	1.66	1.54	1.04	1.48	1.59 +	1.73
1720	1.90	1.33	1.12	1.29	0.95	1.69 +	1.65	0.92	0.83	0.43
1730	1.04	0.82	1.48	1.44	1.18	0.38	1.11	0.90	1.04	0.81
1740	1.33	1.15	0.88	1.54	1.64	1.84	1.98	1.20	0.52	1.26
1750	0.77	0.85	0.45	0.79	0.95	0.83	0.84	0.87 +	1.28	1.03
1760	1.30	1.36	1.33	0.76	1.46	1.07	1.29	1.10	1.01	10.5
1770	1.05	1.50	1.48	0.69 +	0.83	1.03	1.04	0.81	0.48	0.85
1780	0.47	0.60	0.38	0.87	1.28	1.06	1.55	1.93	1.29	1.32
1790	1.16	1.12	1.17	1.62	1.43	1.17	0.64	0.95	0.77	1.34
1800	0.78	0.81	1.27	1.05	0.98	0.82	1.04	0.93	0.84	1.01
1810	0.88	1.01	0.94	0.44	0.51	0.76	0.79	0.65	0.58	0.97
1820	0.72	0.71	0.56	0.66	0.81	1.09	1.47 +	1.17	1.39	0.75
1830	0.92	1.15	1.32	1.37	1.30	1.46	0.83 +	0.97 +	1.21	1.10
1840	1.03	0.54	0.57	0.49	0.81	0.65	0.57	0.36	0.83	1.07
1850	1.14	0.58	1.18	1.17	1.24	1.19	0.78	0.74	1.08−	0.79
1860	0.92 +	0.96	1.09	0.76	0.66	0.87−	1.55	1.38	1.90	1.26
1870	1.30	1.10	1.26	1.24	1.53	1.17	0.87	0.81	0.91	0.37
1880	0.73	0.65	0.76	0.75	0.57	0.80	0.76	0.75	1.06	1.25
1890	1.14	1.01	1.07	1.09	0.94	0.67	0.89	0.93	1.14	0.80
1900	1.02 +	1.43	1.03	1.49 +	1.05	1.58	1.62	1.94	2.30	2.19
1910	1.49 +	1.25	1.39	1.05 +	1.30	1.20	1.57	1.54	0.95	1.80
1920	0.90	....	....	....	....	....	....	....	....	....

Flagstaff High (FLH), 10 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1630	....	....	....	....	....	....	....	4.60	3.80	2.90
1640	3.60	4.40	1.70	2.50	3.00	2.70	3.50	3.80	3.00	3.50
1650	4.30	4.00	3.80	4.20	3.50	4.20	3.90	2.50	2.00	2.30
1660	1.20	0.30	1.00	0.90	0.80	0.80	0.80	0.50	0.70	0.50
1670	0.50	0.50	1.00	1.00	1.10	0.60	0.90	1.10	2.10	1.50
1680	1.80	1.70	1.80	2.50	3.30	2.40	1.90?	2.90	2.00	2.50
1690	2.20	1.50	2.30	1.70	1.60	1.80	1.50	1.30	1.40	2.20
1700	1.70	1.60	1.40	0.90	1.60	2.10	1.60	1.40	1.20	2.00
1710	2.20	1.20	1.20	1.30	1.40	1.40	1.40	0.90	1.10	1.40
1720	1.40	1.30	1.20	1.30	1.20	1.00	1.40	1.60	1.30	1.40
1730	1.30	1.30	1.40	1.40	1.10	0.70	1.20	1.00	1.30	0.90
1740	0.40	1.00	2.00	1.00	1.00	1.10	1.10	1.00	0.50	0.90
1750	0.70	1.10	0.90	1.00	0.80	0.70	1.00	0.90	0.60	0.80
1760	0.80	0.80	0.90	0.80	0.70	0.70	0.80	0.80	0.70	0.70
1770	1.15	2.10	2.55	1.70	2.15	2.15	1.65	1.90	2.05	1.50
1780	1.97	1.93	1.83	2.53	2.37	2.07	2.26	2.63	1.97	2.23
1790	2.40	3.08	2.43	1.83	2.08	1.55	2.12	2.33	2.10	2.37
1800	2.32	2.21	2.14	2.40	2.31	2.09	2.51	1.99	2.21	2.29
1810	2.27	2.04	2.11	1.40	1.87	1.41	1.36	1.44	1.43	1.63
1820	1.51	1.36	1.11	1.36	1.57	1.74	1.86	1.27	1.24	1.53
1830	1.57	1.40	1.67	1.23	1.84	1.47	1.24	1.68	1.73	1.84
1840	1.95	1.40	1.16	1.61	2.08	1.84	1.57	1.61	1.43	1.79
1850	1.58	2.03	2.17	2.45	1.80	2.00	1.94	2.49	2.41	1.69
1860	2.18	1.79	1.87	1.85	1.71	1.87	1.45	1.72	1.92	2.18
1870	2.25	2.01	1.63	2.05	1.58	2.10	1.62	1.81	1.85	2.27
1880	1.20	1.60	1.53	1.81	1.49	1.76	1.61	1.80	1.74	1.92
1890	2.04	1.72	1.94	1.58	1.80	1.85	1.03	1.31	1.45	1.09
1900	1.23	1.18	1.20	1.49	1.55	1.25	1.42	1.74	1.95	1.99
1910	1.87	1.62	1.60	1.70	1.75	1.50	1.22	1.33	1.29	1.18
1920	1.18	1.06	1.23	1.12	0.52	....	....	....	....	....

Flagstaff Shadow (SH), 5 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1710	....	....	....	....	....	....	....	4.80	6.10	5.40
1720	5.90	3.60	4.00	0.90	2.60	3.80	4.10	3.30	3.50	2.00
1730	3.90	2.20	2.60	2.70	4.50	1.20	2.50	1.30	0.40	1.10
1740	2.30	2.10	2.10	3.90	4.30	4.10	4.60	3.70	1.00	3.90
1750	2.20	2.30	0.50	1.30	2.90	2.50	3.50	3.00	3.90	2.95
1760	2.60	1.85	2.40	1.20	3.05	2.45	2.85	1.95	2.20	1.95
1770	1.95	1.65	1.75	0.45	0.80	1.20	1.65	1.00	0.70	0.50
1780	0.45	1.05	1.73	1.33	2.00	0.77	0.53	1.80	0.70	1.43
1790	0.83	1.53	2.23	3.33	2.23	2.45	1.80	2.08	1.33	2.30
1800	0.80	0.83	1.45	0.43	1.03	0.70	1.33	1.23	1.78	1.30
1810	1.53	1.70	1.85	0.50	0.55	0.90	1.62	1.15	0.75	10.8
1820	0.30	1.40	0.62	0.70	1.60	1.80	2.15	2.38	2.76	1.66
1830	2.52	2.45	2.45	2.20	2.18	2.23	1.78	1.55	2.15	2.55
1840	2.15	1.30	1.63	1.38	1.98	1.53	0.65	0.75	1.48	1.60
1850	1.98	1.45	2.25	2.00	1.80	1.80	1.32	0.58	0.80	0.75
1860	1.13	1.35	1.55	1.13	1.08	1.35	2.50	2.75	3.02	2.70
1870	2.23	1.50	1.13	0.63	0.87	0.97	0.65	0.60	0.72	0.60
1880	0.42	0.60	0.75	1.30	1.52	1.98	1.16	1.12	1.52	1.54
1890	1.78	1.76	1.74	1.68	1.60	1.58	0.74	1.10	1.12	0.68
1900	0.70	0.68	0.32	1.38	0.94	1.40	2.48	3.02	2.90	3.28
1910	2.84	2.40	2.02	1.32	2.08	2.06	2.15	1.38	2.06	2.76
1920	2.40	2.02	2.04	1.76	*1.28	....	....	....	....	....

* Incomplete.

Flagstaff Northeast (NE), 4 trees

(Dates prior to 1685 marked "doubtful")

A.D.	0	1	2	3	4	5	6	7	8	9
1670	....	....	....	....	....	....	....	1.10	1.08	2.70
1680	....	2.55	1.33	1.83	0.42	1.05	1.10	2.05	1.90	1.90
1690	1.15	1.92	2.24	2.22	1.60	1.60	0.82	0.65	1.68	1.40
1700	0.45	2.20	0.87	0.38	0.68	1.05	0.55	0.83	0.42	0.55
1710	1.20	1.15	1.50	1.65	1.75	1.95	2.30	2.50	3.48	4.70
1720	4.45	2.40	0.95	1.78	1.46	2.37	4.23	2.76	2.29	1.14
1730	1.13	1.38	1.49	0.56	1.37	0.39	1.26	0.74	1.36	1.02
1740	1.70	1.89	1.08	2.31	2.09	2.72	3.83	3.35	1.10	2.11
1750	1.47	1.53	0.83	1.49	1.82	0.68	1.80	2.03	3.02	3.53
1760	3.42	1.77	2.31	1.18	1.40	1.85	1.98	1.66	1.79	1.39
1770	1.21	1.51	0.90	0.64	0.79	0.93	1.41	1.34	0.75	0.91
1780	0.79	0.73	0.89	1.75	1.33	0.54	0.62	1.27	0.85	0.77
1790	1.00	1.24	1.56	2.12	1.84	1.67	1.83	1.41	0.80	1.08
1800	0.63	0.41	0.47	0.45	1.08	0.46	1.02	0.89	1.12	1.14
1810	1.22	1.55	1.37	0.60	1.44	1.81	1.67	1.67	1.43	1.36
1820	0.87	1.15	0.91	1.31	1.54	1.53	1.98	1.63	2.01	1.21
1830	1.64	1.61	1.59	1.64	0.89	1.38	1.18	1.02	1.59	1.71
1840	1.88	1.46	0.68	1.14	1.55	0.31	0.61	0.12	0.85	0.87
1850	1.06	0.77	1.09	1.07	0.71	0.90	0.74	0.09	0.77	0.40
1860	0.63	0.60	0.58	0.49	0.26	0.57	0.65	0.83	1.20	1.19
1870	0.77	0.40	0.43	0.57	0.62	0.80	0.61	0.26	0.35	0.25
1880	0.33	0.10	0.35	0.29	0.43	0.77	0.63	0.68	0.71	0.72
1890	0.97	0.85	1.12	0.85	1.07	0.95	0.59	0.84	0.70	0.35
1900	0.50	0.41	0.13	0.48	0.13	0.66	0.83	1.32	1.38	1.62
1910	1.51	1.74	1.35	0.94	1.24	1.11	1.12	1.20	1.22	1.29
1920	1.38	1.25	1.27	....	....	....	....	....	....	....

Grand Canyon (GC), 7 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1710	....	....	....	....	....	....	1.25	1.55	2.95	1.20
1720	2.00	2.15	0.60	1.90	0.60	0.90	1.50	1.25	0.95	0.50
1730	0.80	1.15	2.00	1.10	0.60	0.30	0.60	0.45	1.10	0.40
1740	1.25	1.30	0.90	1.30	1.05	1.20	2.05	2.12	0.67	1.90
1750	1.25	0.92	0.35	0.47	0.48	0.47	0.67	0.82	1.27	0.95
1760	1.15	0.92	1.28	0.93	1.83	1.03	1.13	1.35	1.60	0.93
1770	0.77	1.50	1.27	0.58	0.80	0.90	1.30	0.95	0.38	0.92
1780	1.23	0.93	0.50	0.98	1.50	0.53	0.95	1.42	0.78	0.93
1790	0.80	1.13	0.95	2.00	0.76	1.22	0.84	0.70	0.53	1.09
1800	0.45	0.45	0.81	0.44	0.71	0.62	0.44	0.78	0.81	0.64
1810	0.30	0.74	0.96	0.24	0.52	0.50	0.73	0.65	0.31	0.52
1820	0.28	0.61	0.25	0.39	0.52	0.86	0.89	0.87	1.03	0.36
1830	0.49	0.74	0.68	0.85	0.60	0.87	0.54	0.86	0.81	1.11
1840	1.16	0.69	0.42	0.44	0.75	0.13	0.23	0.07	0.55	0.83
1850	0.89	0.61	0.74	0.74	0.87	0.96	0.79 +	0.66	0.84	0.49
1860	0.51	0.44	0.83	0.52	0.31	0.63	1.18	0.85	1.66	1.33
1870	0.80	0.66 −	0.61	0.45	0.90	0.88	0.55	0.48	0.79	0.27
1880	0.28	0.25	0.30	0.35	0.69 +	1.08	0.97	0.50	1.16 +	1.18
1890	1.68	1.66 +	1.66	1.41	0.84	1.17	0.32 +	0.86	0.79 +	0.16 +
1900	0.28 +	0.35	0.37	0.67	0.06	0.61	1.01	1.32	1.23	2.17
1910	1.08	1.39 +	1.07	0.67	1.19	1.07	1.14	0.82	0.39 +	0.89

Dixie Forest (DF), 10 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1610	....	....	....	....	....	....	1.56	1.62	2.20	1.26
1620	1.26	2.26	1.06	1.76	1.00	1.70	1.95	1.85	2.20	2.40
1630	1.85	1.50	1.40	2.50	2.30	2.35	2.60	1.65	2.15	1.40
1640	2.20	1.75	2.25	2.30	2.50	2.20	1.65	2.35	1.85	2.10
1650	2.30	3.10	3.75	1.35	2.60	1.50	2.05	2.20	2.45	2.25
1660	2.28	2.70	2.70	2.05	2.45	1.80	1.85	2.40	1.80	1.95
1670	1.30	2.40	2.45	2.10	2.35	1.65	1.50	2.10	1.75	1.75
1680	2.10	2.15	1.50	2.90	1.60	2.50	1.40	2.10	1.65	1.75
1690	1.15	1.65	1.80	1.65	2.10	2.15	1.75	1.55	1.65	1.95
1700	2.10	1.95	1.85	1.30	1.65	2.10	2.15	0.70	0.55	0.95
1710	1.30	1.55	0.95	0.85	1.10	1.05	1.42	1.35	1.52	1.70
1720	2.10	1.85	1.87	1.80	2.37	1.77	2.31	1.74	1.79	1.02
1730	1.56	1.71	1.21	1.50	1.44	0.35	1.32	1.09	1.35	1.24
1740	1.52	1.56	1.14	1.40	1.45	1.51	1.76	1.76	1.35	1.94
1750	1.26	1.46	0.89	1.21	1.19	1.24	1.02	1.41	1.15	1.11
1760	1.24	1.15	1.09	0.77	0.89	1.13	1.34	1.27	1.11	1.27
1770	1.36	1.30	1.16	1.40	1.46	1.46	1.40	1.17	1.39	1.33
1780	1.38	1.21	1.01	1.22	1.78	1.12	1.14	1.50	1.13	1.68
1790	1.46	1.45	1.62	1.36	1.56	1.17	1.26	1.36	1.18	1.42
1800	1.24	1.44	1.60	1.06	1.24	1.43	1.27	1.24	1.28	1.47
1810	1.32	1.52	1.27	1.16	1.34	1.24	1.30	1.28	1.27	1.30
1820	0.96	1.30	0.94	0.92	0.97	1.26	1.20	1.22	1.53	1.40
1830	1.23	1.48	1.70	1.60	1.16	1.22	1.01	1.20	0.98	1.18
1840	1.33	0.98	0.90	1.04	1.18	1.03	1.17	0.94	1.03	1.53
1850	1.34	1.04	1.12	1.30	1.26	1.35	1.14	1.26	1.22	1.18
1860	1.15	1.02	1.34	1.37	0.91	1.02	1.43	1.41	1.45	1.40
1870	1.61	1.22	1.20	1.10	1.38	1.34	1.00	1.30	1.14	0.68
1880	0.85	0.97	1.17	1.18	1.19	1.58	1.14	1.44	1.42	1.16
1890	1.30	1.45	1.43	1.37	1.52	1.40	1.34	1.43	1.50	1.34
1900	1.30	1.57	1.34	1.38	1.59	1.46	1.59	1.79	1.78	1.66
1910	1.79	1.64	1.60	1.55	1.63	1.61	1.67	1.39	1.34	1.44
1920	1.17	1.21	1.35	1.00	....	....	....	....	....	....

Rim High (RH), 2 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1690	....	....	....	....	....	....	....	0.98	1.22	1.58
1700	1.20	1.26	1.05	1.22	0.75	0.98	1.04	0.55	0.79	1.31
1710	1.42	0.66	0.92	1.19	1.12	1.17	0.97	0.96	1.22	0.98
1720	1.26	0.92	0.60	1.13	0.90	0.82	1.09	0.53	0.70	0.55
1730	0.69	0.60	0.78	0.47	1.00	0.37	0.84	0.74	0.66	0.53
1740	1.03	0.63	0.72	0.80	0.56	0.86	1.12	0.93	0.25	0.79
1750	0.91	0.66	0.40	0.65	0.92	1.04	0.86	0.75	0.86	1.15
1760	1.22	0.70	0.90	0.90	1.55	1.30	1.50	1.80	1.20	1.00
1770	1.45	1.40	0.80	0.90	0.85	0.60	1.00	0.85	1.06	0.83
1780	1.00	1.10	0.63	0.82	1.69	0.80	1.20	1.40	1.08	0.79
1790	0.71	0.79	0.88	1.20	1.01	0.88	0.70	0.65	0.53	0.70
1800	0.65	0.60	0.98	0.93	1.00	1.18	0.75	0.96	1.00	0.92
1810	0.81	1.12	0.87	0.68	0.65	0.90	0.83	0.55	0.69	0.51
1820	0.56	0.55	0.51	0.41	0.45	0.57	0.63	0.48	0.48	0.35
1830	0.52	0.46	0.48	0.45	0.65	0.58	0.70	0.70	0.80	0.73
1840	0.72	0.44	0.57	0.68	0.71	0.29	0.70	0.42	0.68	0.80
1850	0.70	0.70	0.91	0.63	0.70	0.55	0.78	0.61	0.76	0.72
1860	0.72	0.80	0.65	0.66	0.68	0.82	1.20	0.76	1.10	0.48
1870	0.78	0.76	0.73	0.43	0.83	0.83	0.72	0.81	0.98	0.65
1880	0.78	0.80	0.66	0.80	0.82	0.72	0.52	0.80	0.82	0.70
1890	0.85	0.63	0.59	1.02	0.50	0.62	0.88	0.79	0.78	0.78
1900	0.50	0.75	0.48	0.76	0.25	0.75	0.76	0.84	1.06	0.90
1910	0.70	0.80	0.75	0.58	0.80	0.68	0.62	0.82	0.52	0.66
1920	0.59	0.76	0.55	....	....	....	....	....	....	....

Rim Low (RL), 2 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1770	1.00	1.43	1.43	0.98	1.02	1.10	1.35	1.27	0.84	0.71
1780	0.68	0.75	0.51	0.77	1.49	0.92	0.95	1.35	0.97	0.99
1790	0.93	1.27	1.14	1.69	1.00	0.84	0.70	0.95	0.65	0.87
1800	0.72	0.71	0.84	0.50	0.79	0.68	0.83	1.00	1.05	0.95
1810	0.49	1.18	1.16	0.56	0.94	1.13	0.65	0.85	0.77	0.41
1820	0.12	0.70	0.36	0.28	0.85	0.75	1.13	1.43	1.50	1.53
1830	1.29	0.61	1.50	1.22	0.86	1.06	1.08	0.82	0.71	1.52
1840	1.46	0.78	0.78	0.84	0.89	0.62	0.63	0.27	0.83	0.75
1850	0.60	0.78	1.32	0.85	0.73	0.96	0.55	0.28	0.77	0.38
1860	0.58	0.44	0.62	0.39	0.24	0.70	0.60	0.90	1.41	1.44
1870	0.95	0.74	0.66	0.48	0.39	0.86	0.70	0.68	0.93	0.32
1880	0.58	0.41	0.35	0.45	0.92	1.38	0.92	0.78	1.36	1.08
1890	1.25	1.42	0.90	1.26	0.39	1.19	0.44	0.84	0.84	0.60
1900	0.36	0.79	0.06	0.42	0.08	0.95	0.98	1.31	1.85	1.49
1910	1.31	1.41	1.32	0.63	1.45	1.01	1.12	1.28	1.05	1.22
1920	1.33	1.02	....	....	....	....	....	....	....	....

Cibecue (J), 5 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1650	....	....	1.02	1.43	1.10	0.75	1.13	0.86	0.43	0.66
1660	0.80	1.09	1.12	1.40	1.33	1.37	1.11	1.00	0.75	0.63
1670	0.21	1.02	0.77	1.00	0.88	0.80	0.90	0.87	0.67	0.95
1680	1.30	1.43	0.92	1.43	0.27	0.13	1.20	1.40	1.60	1.55
1690	1.66	1.20	1.60	1.05	1.80	1.70	1.00	1.70	0.93	2.83
1700	1.03	0.98	1.24	0.87	1.13	1.35	1.34	0.35	0.55	0.72
1710	1.24	0.68	0.71	0.69	1.35	0.62	0.40	0.90	1.17	0.96
1720	1.10	1.02	0.66	1.03	0.44	0.95	1.15	0.90	0.75	0.33
1730	0.73	0.41	0.90	0.48	0.85	0.18	0.72	0.83	1.10	0.53
1740	1.28	1.16	0.73	1.00	0.82	1.11	1.35	1.62	0.80	1.96
1750	1.33	0.58	0.18	0.40	0.65	0.45	0.48	0.38	0.68	0.72
1760	0.66	0.60	1.18	0.40	1.59	0.81	1.38	0.92	1.16	0.93
1770	0.99	1.22	0.96	0.29	0.86	0.82	0.81	0.62	0.39	0.58
1780	0.27	0.36	0.12	0.59	1.08	0.43	0.69	1.10	0.67	0.59
1790	0.52	0.82	1.08	1.77	0.86	1.06	0.89	0.43	0.52	0.61
1800	0.38	0.27	0.43	0.12	0.47	0.29	0.36	0.44	0.51	0.47
1810	0.29	0.50	0.47	0.39	0.41	0.53	0.68	0.58	0.40	0.12
1820	0.04	0.34	0.03	0.28	0.28	0.48	0.33	0.13	0.72	0.44
1830	0.38	0.42	0.43	0.68	0.62	0.50	0.52	0.44	0.62	0.91
1840	0.68	0.42	0.40	0.33	0.70	0.20	0.20	0.12	0.15	0.46
1850	0.55	0.45	0.82	0.73	0.43	0.47	0.88	0.57	0.88	0.55
1860	0.90	0.49	1.03	0.77	0.26	0.92	0.91	1.01	1.28	1.23
1870	0.84	0.38	0.83	0.38	0.47	0.78	0.57	0.49	0.44	0.60
1880	0.43	0.41	0.42	0.49	0.57	0.66 +	0.64	0.46	0.57	0.59
1890	0.90	0.82	0.78	0.41	0.20	0.34	0.44	0.40	0.40	0.37
1900	0.12	0.35	0.10	0.21	0.12	0.47	0.71	0.76	0.91	1.01
1910	0.76	1.04	0.65	0.42	1.03	0.84	0.96	1.17	0.90	0.88
1920	0.67	....	....	....	....	....	....	....	....	....

Pinal (PNL), 3 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1760	0.73	1.10	1.35	0.72	1.30	0.92	0.65	0.60	0.90	0.80
1770	0.80	1.15	0.80	0.45	0.55	0.70	0.42	0.50	0.65	0.60
1780	0.63	0.55	0.35	0.58	0.68	0.63	0.78	1.05	0.55	0.92
1790	0.75	0.58	0.73	0.60	0.68	0.55	0.68	0.65	0.75	0.98
1800	0.95	0.75	0.95	0.85	0.78	0.96	0.69	0.64	0.86	0.93
1810	0.67	0.46	0.50	0.42	0.59	0.56	0.47	0.62	0.44	0.38
1820	0.27	0.69	0.36	0.33	1.08	1.11	0.98	1.00	1.23	0.88
1830	1.36	0.92	1.37	1.37	0.83	0.90	0.87	0.69	0.90	1.14
1840	0.89	0.47	0.84	1.09	1.36	0.84	0.90	0.44	1.15	1.00
1850	1.35	1.52	2.17	1.11	0.94	0.84	0.86	0.79	1.07	0.73
1860	0.91	0.75	0.94	0.42	0.33	0.80	1.15	0.55	0.95	0.99
1870	0.57	0.43	0.56	0.44	0.49	0.88	1.03	0.78	0.95	0.90
1880	0.48	0.95	0.80	0.60	0.85	0.87	0.50	0.64	0.48	0.41
1890	0.87	0.79	0.36	0.51	0.47	0.46	0.57	1.07	0.83	1.01
1900	0.015	0.36	0.73	0.56	0.42	1.09	1.28	1.22	2.14	2.13
1910	0.66	0.68	0.64	0.40	0.54	0.68	0.53	0.41	0.27	0.32
1920	0.36	0.47	0.43	0.23	....	....	....	....	....	....

Santa Catalina (SC), 8 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1560	....	....	....	....	....	....	....	1.02	1.46	1.85
1570	1.47	1.67	0.87	1.20	0.98	1.42	1.42	1.27	1.03	0.88
1580	1.08	1.63	1.46	1.10	1.11	1.60	1.50	1.20	1.20	1.30
1590	0.68	0.95	1.17	1.16	1.04	1.10	1.11	1.40	1.22	1.14
1600	1.75	1.44	1.51	1.20	0.93	1.38	0.91	1.45	1.29	1.24
1610	1.60	1.10	0.80	1.23	1.21	0.87	1.39	1.19	0.98	1.43
1620	1.31	0.85	0.91	0.81	0.68	0.47	0.19	0.26	0.30	0.39
1630	0.65	0.78	1.30	2.02	1.73	1.10	1.56	1.16	1.03	1.35
1640	1.21	0.90	0.96	0.72	0.68	0.83	1.07	1.65	1.53	1.00
1650	1.81	0.67	0.72	0.89	1.00	1.40	1.00	0.59	0.65	0.61
1660	0.34	0.65	0.41	0.51	0.55	0.80	1.34	1.04	2.02	1.86
1670	1.80	1.74	1.48	1.49	1.19	1.52	1.54	1.25	1.71	0.94
1680	0.71	1.51	1.05	1.10	1.15	0.87	1.17	1.22	1.44	0.96
1690	1.48	1.13	1.15	1.06	0.74	0.48	0.78	1.06	0.43	1.08
1700	0.89	0.80	1.07	1.12	1.09	0.81	0.79	0.85	0.99	0.96
1710	0.82	0.58	0.70	0.85	0.65	0.59	0.48	0.59	0.68	0.85
1720	0.66	0.84	0.78	0.79	0.84	0.81	0.83	0.91	0.83	1.46
1730	1.36	1.51	1.51 +	1.39	1.11	1.00	1.06	1.20	1.17	0.88
1740	0.81	1.21	0.95	1.08	0.77	0.77	0.80	0.76	0.41	0.73
1750	0.74 −	0.68 +	0.51	0.56	0.80	0.91	0.82	0.98	0.96	1.01
1760	0.86	1.06	0.98	1.03	1.18	1.16	1.12	1.10	1.01	0.96
1770	1.09	1.02	1.04	0.98	1.07	1.14	1.14	1.19	1.38	1.09
1780	1.17	1.32	1.01	1.19	1.18	1.13	0.79 +	0.78 −	0.75	0.65
1790	0.72	0.97	1.29	1.29	1.39	1.13	0.87	0.95	0.83	0.99
1800	1.20	1.11	0.95	0.99 +	1.09	1.21	1.41	1.21	1.04	1.37
1810	1.29	1.21	1.04	1.10	1.32	1.33	1.32	1.03	0.80	0.73
1820	0.85	0.74	0.65	0.83	0.84	0.91	1.08	1.01	0.90	1.12
1830	1.28	0.82	1.24	0.82	0.56	0.94	0.67	0.82	0.93	1.08
1840	1.14	0.94	0.94	1.34	1.59	1.80	1.20	1.42	1.38	1.08
1850	1.19	0.72	0.96	1.16	0.82	0.51	0.78	0.97	0.95 −	0.69 −
1860	1.13	1.07	0.74	0.89	0.70	0.50	0.83	0.51	0.54	0.53
1870	0.64	0.74	0.89	0.79	0.77 +	0.97	0.89	0.80	1.13	1.35
1880	0.94 +	0.88	1.02	0.91	1.10	1.18	0.88	0.82	1.01	0.98
1890	0.95	0.68	0.74	0.96	0.81	0.80	0.88	0.70	1.09	0.89
1900	0.78	0.89	0.76	0.76	0.74	0.96	0.53	0.74 +	0.95	0.68
1910	0.46	0.57	0.58	0.62	0.83	0.45	0.65	0.79	0.52	0.75
1920	0.79 +	....	....	....	....	....	....	....	....	....

Santa Rita (SR), 5 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1670	0.82	0.52	0.47	0.64	0.74	1.00	2.18	1.20	1.87	1.00
1680	1.07	1.20	1.09	0.95	1.14	1.11	1.13	1.41	1.43	0.85
1690	0.59	0.77	0.98	1.12	1.38	0.80	0.72	1.05	1.18	1.27
1700	1.00	1.20	1.00	1.58	1.30	1.04	0.91	0.85	1.12	1.14
1710	1.30	0.72	0.72	0.44	1.04	0.84	0.85	1.12	1.25	1.22
1720	1.31	1.06	1.06	1.10	1.40	1.18	1.51	0.61	1.20	1.02
1730	0.97	1.61	1.68	0.86	0.87	0.56	1.18	0.88	0.87	0.58
1740	0.86	0.78	1.03	1.93	1.74	1.21	1.42	1.70	0.62	0.46
1750	0.78	0.12	0.69	0.40	0.42	0.66	0.78	1.00	1.10	0.76
1760	1.08	1.22	0.66	1.11	1.01	0.79	1.04	1.04	1.13	0.98
1770	0.98	0.67	0.90	0.53	0.50	0.55	0.60	0.75	0.59	0.70
1780	0.80	0.67	1.02	0.90	1.10	0.70	0.62	0.81	1.01	0.99
1790	0.69	0.66	0.85	0.83	0.57	0.66	0.78	0.39	0.39	1.08
1800	0.56	0.23	0.77	1.03	1.18	1.28	1.11	1.22	0.87	1.30
1810	1.58	1.31	1.54	1.06	1.51	1.49	1.47	0.97	1.22	0.41
1820	0.61	0.62	0.68	0.82	0.95	0.89	1.50	1.42	1.45	1.32
1830	1.35	1.14	1.30	1.05	0.78	0.97	0.83	0.95	0.96	1.41
1840	1.53	0.84	0.62	1.12	1.55	1.32	1.05	0.39	0.58	0.78
1850	0.95 +	0.87	1.03	1.32	1.26	1.33	1.29	0.97	1.00	1.12
1860	1.23	1.17	0.86	0.81	0.72	0.85	0.79	0.68	0.94	0.98
1870	0.80	0.77	0.65	0.78	0.64	0.77	0.44	0.88 +	0.80	0.75
1880	0.53	1.02	1.22	1.19	1.04	1.05	0.46	0.54	0.92	0.76
1890	0.75	0.66	0.39 +	0.37	0.53	0.43	0.97	0.90	1.22	1.21
1900	0.77	0.91	0.63	1.13	0.71	1.24	1.09	1.25	1.39	1.13
1910	0.84	1.30	0.71	0.96	1.30	0.92	1.06	1.15	0.91	1.19
1920	0.84	0.62	....	....	....	....	....	....	....	....

ROCKY MOUNTAIN ZONE

Yellowstone (Y), 5 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1690	....	....	....	1.00	1.16	1.16	0.88	0.66	1.02	0.77
1700	0.74	1.09	1.00	1.12	0.98	1.06	0.95	0.79	1.00	1.29
1710	1.00	0.95	1.22	1.16	1.16	1.09	1.12	0.81	0.83	0.87
1720	0.89	0.87	0.80	1.06	0.97	1.00	0.95	1.06	1.26	1.23
1730	1.02	0.85	1.03	1.21	1.24	0.95	0.93	1.46	1.08	1.11
1740	1.00	1.15	1.03	0.85	0.75	1.05	1.13	1.17	1.20	1.18
1750	1.04	1.05	1.13	1.13	0.91	0.95	1.06	1.05	1.11	1.50
1760	1.36	0.98	0.98	1.11	1.01	1.11	1.01	1.25	1.37	1.35
1770	1.10	1.04	1.16	1.21	1.36	1.00	1.43	1.29	1.28	1.17
1780	1.43	1.00	0.87	0.86	0.97	0.78	0.94	1.16	1.03	1.29
1790	1.03	1.33	1.27	1.35	1.17	1.38	1.16	0.90	0.98	0.84
1800	1.00	0.94	1.00	0.91	1.10	0.93	0.89	0.75	1.03	0.79
1810	0.92	0.88	0.93	1.12	0.91	1.26	1.24	1.48	1.36	1.27
1820	1.40	1.12	1.04	0.96	1.02	0.96	1.15	1.33	1.11	1.13
1830	1.06	1.13	0.97	0.97	1.22	1.14	1.14	1.18	1.08	1.19
1840	1.04	1.35	1.47	1.78	1.55	1.10	1.32	1.02	0.94	1.04
1850	1.00	1.09	0.83	1.09	1.08	0.82	0.92	1.12	0.94	1.01
1860	1.13	1.37	1.01	1.10	0.87	0.83	1.04	1.00	1.15	0.98
1870	0.88	0.84	0.89	0.86	0.97	0.94	0.95	1.11	1.17	1.38
1880	1.12	1.17	1.20	0.75	1.05	1.09	1.09	1.12	1.26	1.15
1890	1.18	1.19	1.14	1.11	1.15	1.12	0.92	1.17	0.95	0.74
1900	1.03	0.96	0.74	0.83	0.83	0.98	0.77	0.90	1.02	0.98
1910	1.16	1.06	0.99	1.09	1.08	0.89	0.84	0.79	0.88	0.87
1920	0.87	....	....	....	....	....	....	....	....	....

Laramie, Wyoming (LW), 3 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1750	....	....	....	....	1.95	1.20	0.55	0.35	0.65	0.80
1760	0.80	1.75	0.95	1.15	0.95	1.10	1.20	1.35	1.70	1.80
1770	0.90	1.35	1.00	0.80	1.05	1.20	1.20	0.50	1.50	1.50
1780	1.60	1.90	1.00	1.30	2.15	1.95	1.10	2.05	0.85	0.50
1790	1.40	1.30	1.15	1.70	2.00	1.25	1.20	0.30	0.45	1.60
1800	1.60	1.30	2.40	2.55	0.70	0.45	0.95	0.50	1.05	0.85
1810	1.30	1.25	1.05	1.05	1.10	1.00	1.05	1.20	1.00	1.25
1820	0.55	1.20	1.65	1.25	0.60	1.40	1.10	1.05	1.85	1.32
1830	0.96	0.90	0.94	1.12	1.16	1.37	1.58	1.78	1.69	1.84
1840	1.52	1.46	0.53	1.89	1.48	0.86	1.04	0.61	0.57	0.98
1850	1.05	0.72	1.14	1.56	1.09	0.59	0.59	0.59	1.16	1.31
1860	1.51	0.43	1.63	0.56	1.05	0.92	1.54	1.53	1.68	1.86
1870	1.63	0.91	1.75	1.31	0.66	1.56	1.36	0.65	1.63	0.92
1880	0.26	0.18	0.99	0.78	0.81	0.98	0.82	0.78	1.19	1.32
1890	1.03	1.83	1.24	0.93	0.93	1.21	1.08	1.46	1.42	1.21
1900	0.92	1.39	1.18	1.66	1.65	1.46	2.14	1.99	1.84	1.72
1910	1.43	1.18	1.31	1.74	1.46	1.93	1.00	1.55	1.48	0.58
1920	1.47	1.60	1.15	1.62	1.41	....	....	....	....	....

Clements' Pike's Peak (C), 8 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1770	....	....	....	....	....	....	....	....	1.41	1.86
1780	1.78	2.38	2.16	1.26	1.62	1.41	1.79	1.75	2.00	1.41
1790	2.27	2.20	2.56	2.52	2.42	2.36	2.46	1.91	1.83	1.23
1800	1.73	1.14	1.65	2.13	1.60	1.12	1.77	1.77	1.32	1.53
1810	1.60	1.55	1.92	1.65	1.31	1.71	1.95	1.68	1.53	1.71
1820	1.54	1.31	1.19	1.33	0.913	1.19	1.45	1.48	1.80	1.45
1830	1.34	1.68	1.08	1.41	1.49	1.72	1.83	1.95	2.31	2.08
1840	2.15	1.51	1.32	1.58	1.65	1.44	1.39	1.27	1.41	1.48
1850	1.25	0.567	1.49	1.47	1.76	1.17	0.92	1.35	1.81	1.07
1860	1.32	0.523	1.00	0.603	1.10	0.81	1.23	1.36	1.13	1.68
1870	1.08	0.863	1.09	1.08	1.06	1.22	1.18	1.08	1.37	0.937
1880	0.357	0.891	0.801	0.885	0.672	0.782	0.702	0.693	0.654	0.794
1890	0.57	0.705	0.734	0.439	0.581	0.720	0.594	0.796	0.970	0.351
1900	0.808	0.729	0.823	0.952	1.31	1.12	1.01	0.979	0.623	0.953
1910	0.917	0.668	0.842	0.95	1.08	1.18	0.994	0.734	0.67	0.81

Pike's Peak, 11,500 Feet (PPT), 5 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1730	....	....	....	....	0.81	0.78	0.70	0.79	0.82	0.91
1740	0.98	1.12	1.16	1.00	1.18	1.00	1.09	1.20	0.82	1.15
1750	1.18	1.06	1.09	1.10	1.05	0.92	1.08	0.98	1.08	1.36
1760	1.10	0.99	1.22	1.14	1.03	1.27	1.09	1.12	0.81	0.86
1770	0.75	0.86	0.97	0.74	0.93	0.84	0.97	0.95	0.93	1.02
1780	1.18	1.01	0.82	1.07	1.21	1.06	1.13	1.09	0.90	0.96
1790	1.02	0.90	1.18	0.95	1.05	0.96	1.03	1.05	1.15	1.16
1800	0.92	0.94	1.05	0.94	0.80	0.68	0.78	0.94	0.80	0.87
1810	1.01	0.95	0.92	0.85	0.99 +	0.79 +	0.89 +	1.07	0.83	0.97
1820	0.90	0.98	0.90	0.84	0.94	0.98	0.94	1.07	0.86	0.83
1830	0.96	0.91	1.04	1.11	1.07	0.94	0.73	1.06	0.90	0.80
1840	0.90	1.00	0.73	0.95	1.03	0.92	0.85	0.85	1.05	1.02
1850	0.88	0.45	0.81	0.88	0.90	0.92	0.97	0.89 +	0.84	0.85
1860	0.90	0.85	1.01	1.03	1.04	0.82	1.07	1.29	1.09	0.51
1870	1.47	1.21	1.17	1.29	1.36	1.40	1.57	1.27	1.32	1.17
1880	1.00	1.23	1.00	1.12	1.15	1.17	1.35	1.22	1.34	1.27
1890	1.02	1.01	1.01	0.79	0.84	0.77	1.01	1.02	1.07	0.76
1900	0.94	0.91	0.87	0.95	0.83	0.80	0.73	1.01	0.69	0.87
1910	1.01	0.77	0.85	0.86	0.79 +	0.78	0.95	0.91	1.02	0.95
1920	0.77	....	....	....	....	....	....	....	....	....

Pike's Peak, 9,500 Feet (PPB), 3 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1690	....	....	....	1.35	1.07	1.38	1.14	0.96	1.18	1.24
1700	1.26	1.39	1.04	1.17	1.06	1.18	1.22	1.21	1.26	1.08
1710	1.30	1.13	1.25	0.84	1.13	0.89 +	1.00	1.18	1.26	1.10
1720	1.13	1.18	1.22	1.17	1.15	0.86	0.87	0.66	0.84	0.92
1730	0.88	1.02	1.02	0.93	1.07	0.57	0.72	0.86	0.92	1.21
1740	1.32	1.27	0.68	1.14	0.99	0.65	1.19	1.22	0.74	0.85
1750	0.76	0.80	0.72	0.75	0.23	0.75	0.62	0.89 +	0.79	0.89
1760	0.67	0.77	0.99−	0.24	0.87	0.71	0.97	0.98	1.12	1.23
1770	1.49 +	1.37	1.57	1.84	1.67	1.17	1.16	1.31	1.12	1.23
1780	1.11	0.85	0.94	1.03	0.99	1.30	0.85	0.88	1.05	0.32
1790	1.04	0.81	0.98	1.06	1.18	1.09	1.04	1.07	1.17	0.96
1800	1.20	0.80	1.27	0.82	0.96	0.75	0.71	0.86	0.69	0.74
1810	0.87	0.75	0.88	0.86	0.89	0.88	0.99 +	0.99 +	0.62	0.77
1820	0.70	0.53	0.70	0.66	0.66	1.07	0.84	0.83	0.90	0.75
1830	0.64	0.91	0.54	0.95	0.80	0.88	0.81	0.87	0.79	0.67
1840	0.54	0.49	0.49	0.60	0.49	0.43	0.81	0.68	0.65	0.45
1850	0.62	0.15	0.09	0.24	0.32	0.54	0.70	0.69	0.72	0.64
1860	0.82	0.62	1.08	0.85	1.23	0.96	1.69 +	1.08	0.93	1.60
1870	1.70	1.27	1.89 +	2.19	1.86	1.68	2.08	1.50	1.68	1.17
1880	0.72	1.14	1.17	1.53	1.49	1.59	1.52	1.59 +	1.97	2.13
1890	1.67	1.74	1.78	0.79	1.66	1.67	1.27	1.33	1.39 +	0.55
1900	1.48	1.58	1.36	1.56	1.07	1.37	1.18	1.12	0.67	1.21
1910	1.24	1.24	1.19	1.18	1.43	1.31	1.44	1.04	0.84	0.90
1920	0.72	....	....	....	....	....	....	....	....	....

Pike's Peak, High North Transect (HNT), 10 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1650	....	....	....	....	....	1.78	1.72	1.76	1.56	1.14
1660	1.85	1.32	1.42	1.32	0.99	1.13	0.76	0.99	0.55	1.02
1670	0.78	1.01	1.10	1.39	1.19	0.46	0.78	0.88	1.25	1.25
1680	1.82	1.35	0.41	0.49	0.62	0.54	0.88	0.93	1.07	1.30
1690	0.68	0.98	1.50	1.20	0.72	0.89	0.92	1.07	0.83	0.88
1700	0.87	1.37	1.37	1.24	1.13	0.98	1.33	0.87	1.02	0.73
1710	1.34	0.99	1.43	1.15	1.52	0.55	0.74	0.85	1.04	1.04
1720	1.36	1.07	1.09	1.00	1.11	1.34	1.58	0.79	1.14	0.98
1730	0.54	0.48	0.76	0.88	0.87	0.73	0.65	0.75	0.83	1.29
1740	1.09	0.78	0.36	0.81	0.81	0.48	1.11	1.17	0.48	0.62
1750	0.69	0.93	0.69	0.65	0.56	0.64	0.42	0.69−	0.49	0.71
1760	0.67	1.16	0.90	0.62	0.89−	0.85	1.24	0.91	1.60	1.33
1770	1.37	1.86	1.59 +	1.32	1.19 +	1.14	1.27	1.00	0.86	1.26+
1780	0.74 +	1.05	0.81	1.21	1.09 +	1.27	1.12	1.23	1.39+	0.57
1790	1.37	1.24	1.17	1.27	1.11	0.91	1.19 +	1.06	0.79+	0.99+
1800	1.31	0.79 +	1.37 +	1.39−	1.24	0.63	1.21	1.20	0.64−	0.88−
1810	1.25−	1.20	1.29	1.22	1.48	1.24	1.23	1.11	0.71	1.14+
1820	0.70	0.61	0.57	0.69	0.40	0.66	0.90 +	1.12	1.28	0.96
1830	0.80	1.13	0.65	1.07	1.05	1.63	1.29 +	1.27 +	1.58	1.52
1840	1.73	1.04	0.98 +	1.32	1.22	1.06	1.16−	0.91	0.93	0.91
1850	0.81−	0.29−	0.87	0.81	0.93 +	1.02	1.04	1.31	1.49	1.12
1860	1.56	0.85 +	1.10	0.64	1.16	0.69	1.02	1.04	0.98	1.41
1870	1.09	0.88 +	1.55 +	1.19	1.21	1.04−	1.41	1.02−	1.45	0.96−
1880	0.41	0.76−	0.97	1.07−	0.71	0.79 +	0.77	0.80	0.80	1.12
1890	0.93	0.79	0.76−	0.59 +	0.83	1.03	1.04	0.84 +	1.01	0.32 +
1900	0.82	0.78	0.84	0.97	1.05	0.83	0.92	1.05	0.65−	1.03
1910	0.93−	0.84	0.74	0.88−	0.92	0.99	0.89	0.71	0.86 +	0.79 +
1920	0.61	....	....	....	....	....	....	....	....	....

Pike's Peak, Low North Transect (LNT), 7 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1640	....	....	....	....	0.72	0.60	0.98	1.13	1.10	1.20
1650	0.68	1.18	1.15	1.13	0.33	1.33	1.38	1.33	1.17	0.56
1660	1.45	1.48	1.16	1.00	0.80	1.32	0.72	0.89	0.68	0.87
1670	0.77	1.18	1.17	1.22	1.02	0.57	0.41	0.48	0.79	0.70
1680	0.98	0.55	0.60	0.72	0.56	0.33	0.70	0.73	0.96	1.06
1690	0.54	0.81	1.15	0.98	0.61	0.87	0.80	1.05	0.81	0.81
1700	0.79 +	0.89 +	0.82	0.89	0.86	1.00	1.07	0.92	0.79	0.95
1710	1.27	0.89	0.98	0.96	1.12	0.67	0.83	0.68	0.65	1.17
1720	1.26	1.25	1.16	0.86	0.91	0.75	0.93	0.76	0.88	0.79
1730	0.56	0.39	0.56	0.59	0.51	0.56	0.49	0.51	0.55	0.83
1740	0.84	0.82	0.69	0.89	1.07	0.72	1.06	1.02	0.48	0.69 +
1750	0.71	0.82	0.89	1.10	0.89	1.03	0.85	1.29	0.56	0.69 +
1760	0.71	0.89	1.07	0.87	0.79	0.73	0.91	0.80	0.96	0.72
1770	0.82	1.00	1.25	1.20	1.07	0.84	1.01	0.90	0.85	0.90
1780	0.63	0.93	0.78	0.93	0.86	0.86	0.96	1.04	1.06	0.52
1790	1.02	0.98	1.09	0.98	0.86	0.88	0.91	0.81	0.57	0.86
1800	0.91	0.70	1.20	1.09	0.85	0.71	0.93	0.99	0.71	0.69
1810	0.87	0.75	0.80	0.85	1.05	0.88	1.02	1.14	0.78	0.78
1820	0.62	0.58	0.57	0.51	0.50	0.70	0.77	0.98	0.96	0.80
1830	0.64	0.91	0.50	0.73	0.71	0.68	0.81	0.90	1.02	0.86
1840	0.96	0.66	0.63	0.77	0.81	0.68	0.98	0.79 +	0.91	0.75
1850	0.86	0.24	0.87	0.96	1.05	1.16	0.90	1.08	1.24	1.09 +
1860	1.07	0.69	1.03	0.58	1.17	0.83	1.01	1.09	0.85	1.32
1870	1.05	0.85	1.18	1.19	0.96	0.93	1.09	0.92	1.13	0.71
1880	0.42	0.88	0.95	0.86	0.57	0.68	0.71	0.76	0.75	0.73
1890	0.61	0.78	0.85	0.64	0.78 +	0.82	0.72	0.92	1.07	0.39−
1900	0.90	0.77 +	0.88 +	1.00	0.98−	0.87	0.88	0.87 +	0.69	1.11
1910	0.97	0.79	0.91	1.04	1.25	1.21	1.09 +	0.91	0.75	0.95 +
1920	0.70	....	....	....	....	....	....	....	....	....

Pike's Peak, South Transect (ST), 8 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1570	1.40	2.15	2.03	1.12	1.37	0.84	0.73	0.78	0.70	0.68
1580	0.61	1.17	0.93	1.00	1.09	1 07	1.20	0.65	0.63	0.76
1590	0.92	1.00	0.90	0.85	0.95	0.99	0.81	1.02	0.92	1.00
1600	1.18	0.96	0.91	0.92	1.35	0.76	0.73	0.93	0.73	0.95
1610	1.19	1.04	0.66	0.98	0.72	0.98	0.98	0.96	1.19	1.25
1620	0.91	0.80	0.85	1.12	1.19	1.09	1.10	0.82	0.95	1.09
1630	1.10	0.75	1.36	1.32	1.36	0.98	1.13	1.20	0.25	0.16
1640	0.36	0.29	0.42	0.20	0.36	0.41	0.55	0.45	0.66	0.77
1650	0.80	0.87	0.64	0.95	0.82	1.28	1.27	1.47	1.41	1.16
1660	1.44	1.53	1.44	1.35	1.08	1.15	0.97	0.42	0.32	0.60
1670	0.53	0.65	0.68	0.61	0.78	0.68	0.27 +	0.22	0.52	0.52
1680	0.46	0.51	0.70	0.62	0.74	0.83	0.96	1.01	1.14	1.17
1690	1.43	1.01	1.25	1.02	0.95	1.05	1.15	1.17	1.27	1.16
1700	1.48	1.12	1.19	1.23	1.42	1.58	1.28	1.33	1.18	1.33
1710	1.49	1.46	1.38	1.37	1.84	1.01	0.95	0.99 +	1.27	1.49 +
1720	1.45	1.12	0.78	0.62	0.89	1.00	1.01	0.81	0.95	1.27
1730	1.35	0.56	0.22	0.49	0.49	0.80	0.63	0.82	0.86	1.13
1740	1.05	1.06	0.91	1.12	0.98	0.77	0.82	0.95	0.88	0.73
1750	0.62	0.79	0.72	1.05	0.68	0.88	1.25	1.12	0.09	0.18
1760	0.55	0.68	0.74	0.70	0.73	0.66	0.77	1.14	0.84	0.97
1770	0.73	0.93	1.14	1.09	1.07	1.13	1.49	1.52	1.44	1.48
1780	1.01	1.26	0.99−	1.20	1.37	1.29	1.28−	1.21	1.54−	1.30
1790	1.46	1.30	1.39 +	1.65	1.57	1.60	1.71	1.25	0.99 +	1.17
1800	1.25	0.91	1.18	1.17	1.34	1.19	1.29 +	1.31	1.23	1.36−

Pike's Peak, South Transect (ST), 8 trees—Continued

A.D.	0	1	2	3	4	5	6	7	8	9
1810	1.29	1.35	1.59	1.34	1.65	1.42	1.71	1.70	1.38	1.14
1820	1.24	1.11	1.16	1.31	0.94−	1.19−	1.32	1.42	1.37	1.11
1830	0.94	1.17	0.74	0.88 +	0.88+	1.07+	0.97	1.04	1.16−	1.04
1840	1.09−	1.04	0.99 +	1.06	1.03	0.89+	1.08−	0.92	0.90	0.88
1850	0.98+	0.43−	0.95	0.96	1.15	1.07	0.81	0.95 +	1.12	0.78
1860	0.81	0.77	0.80	0.66	0.93	0.76	0.83	0.81	0.86 +	0.89+
1870	0.87−	0.74	0.89	0.98	0.81	0.92	0.99 +	0.88 +	1.11	0.76−
1880	0.73	0.76	0.80	0.59 +	0.56	0.50	0.68 +	0.76	0.71	0.73
1890	0.71	0.82	0.79	0.80	0.97	0.95	0.91	0.99 +	0.98	0.49+
1900	0.87	0.71	0.87	1.05	0.86	0.81	0.64	0.67	0.56	0.79+
1910	0.70	0.63	0.84 +	0.91	0.82	0.87	0.79 +	0.73	0.66 +	0.76+
1920	0.69 +	....	....	....	....	....	....	....	....	....

Pike's Peak, Brook, Douglas Fir and Pine (BDF), 6 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1780	....	....	0.64	0.61	0.58	0.88	0.87	1.18	1.36	0.73
1790	1.13	1.37	1.65	1.20	1.08	1.10	1.33	1.28	0.38	0.32
1800	0.60	0.59	0.90	1.01	1.28	0.87	1.26	1.33	1.21	1.03
1810	1.22	1.07	1.30	1.11	1.17	1.15	1.07	0.89	0.62	0.80
1820	0.82	0.73	0.71	0.67	0.60	0.83	1.20	1.32	1.45	1.33
1830	1.24 +	1.22	0.92	0.97	0.94	1.00	0.87	1.05	0.96	1.05
1840	1.13	0.67−	0.64	0.81	0.84	0.77	0.84	0.87 +	0.96	0.92 +
1850	0.90	0.58+	1.05	1.20	1.41	1.06	0.73	1.12 +	1.39 +	1.20
1860	1.15	0.75	1.02	0.62	0.90	0.59	0.97	1.00	0.78	1.13
1870	0.94	0.79	0.90	0.76	0.93	0.94	0.99	0.84	0.93	0.71
1880	0.35	0.79−	0.88	0.76	0.80	0.77	0.77	0.70	0.78	0.83
1890	0.75	0.76	0.71	0.58	0.76	0.94	0.80	0.94	0.95	0.46
1900	0.53−	0.65+	0.67	0.92	1.10	1.11	0.94	1.08	0.53	1.01
1910	1.03−	0.68−	0.81	1.03−	1.03−	1.37	1.25	0.73	0.64	1.00
1920	0.63−	....	....	....	....	....	....	....	....	....

Pike's Peak, Brook, Engelmann Spruce (BES), 4 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1770	....	....	....	....	....	1.11	0.78	1.07	1.09	1.15
1780	1.35	1.00	1.39	1.34	1.12	1.04	1.04	1.02	0.92	0.92
1790	1.04	1.08	1.43	1.07	1.11	1.13	1.12	1.00	0.98	0.74
1800	1.11	0.69 +	0.99	1.17	1.05	0.82	0.88 +	1.02	0.78	0.97
1810	0.87	0.97	1.00	0.86	1.00	1.09	1.07	1.19 +	1.00	1.10
1820	0.73	0.61	0.56	0.64	0.46	0.80	1.07	1.17	1.31	1.10
1830	0.95	1.11	0.74	0.72	0.81	1.00	1.19	1.09	1.15	1.11
1840	1.17 +	1.26	0.92	1.35	1.14	1.07	1.02	0.93	0.84	0.94
1850	0.87	0.64	0.74	0.82	0.97	0.99	0.66	0.61	0.81	0.38 +
1860	0.72	0.43	0.63	0.66	0.70	0.50	0.60	0.70	0.80	0.90
1870	1.09 +	1.10	1.10	1.00	1.03 +	1.07 +	1.09	1.09	1.42	1.40
1880	1.16	1.25	0.94	1.08	1.05	1.33	1.09	1.40	1.32 +	1.42
1890	1.06	0.84 +	0.79	0.53	0.71	0.87	0.83 +	1.01	1.12	0.82
1900	1.28	1.14	1.15	1.24	0.85	0.83	0.62	0.63	0.74 +	0.86
1910	0.76 +	0.93	0.64	1.15	1.16−	1.26	1.14	0.71	0.60	0.73
1920	0.57	....	....	....	....	....	....	....	....	....

Cloudcroft, New Mexico (CC), 3 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1730	....	....	....	....	....	....	1.21	1.27	1.27	0.90
1740	1.13	1.73	1.12	1.60	2.11	2.23	2.88	3.49	1.69	2.11
1750	1.88	2.62	0.87	2.10	2.08	2.42	2.45	3.02	3.39	2.81
1760	2.83	3.46	2.96	1.67	2.72	2.87	3.78	2.06	1.42	2.70
1770	2.10	2.48	1.92	2.13	2.21	1.96	2.74	2.34	1.70	2.47
1780	1.82	1.92	1.05	1.48	2.26	1.48	1.80	2.37	2.03	1.33
1790	2.51	2.29	2.87	3.11	2.28	1.58	2.71	1.97	1.34	2.40
1800	2.49	1.91	2.18	2.42	2.15	2.62	2.70	1.83	2.09	1.78
1810	1.98	2.00	1.33	2.01	2.24	2.86	2.26	1.42	1.88	0.95
1820	0.84	0.66	1.00	1.39	1.49	1.30	1.44	1.96	1.13	1.96
1830	1.17	0.91	1.30	1.35	1.74	1.22	0.95	0.54	0.61	0.90
1840	1.01	0.70	0.54	0.58	1.05	0.91	1.14	0.45	0.85	0.71
1850	0.40	0.38	1.05	1.08	1.13	0.68	1.37	0.92	1.07	0.32
1860	0.66	1.38	0.45	1.09	0.85	0.96	1.28	1.12	1.89	2.14
1870	1.12	1.52	1.60	1.24	1.18	1.38	2.03	1.31	1.29	1.13
1880	1.15	1.28	1.88	1.66	2.05	2.13	1.58	2.04	1.39	1.51
1890	1.66	1.32	0.75	0.56	0.81	1.06	0.92	1.20	1.96	1.08
1900	1.38	1.19	0.87	1.41	0.51	1.11	0.87	1.48	0.99	0.73
1910	0.72	1.25	1.01	1.20	1.27	0.70	1.17	1.38	1.36	1.32
1920	1.28	....	....	....	....	....	....	....	....	....

Santa Fe, New Mexico (SF), 6 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1740	....	....	....	....	....	....	....	....	....	4.94
1750	3.12	3.48	3.72	3.20	5.18	5.56	2.72	3.52	2.80	3.66
1760	2.80	5.52	4.70	2.88	5.00	3.40	4.94	4.32	2.64	2.96
1770	1.98	3.28	2.38	1.48	2.08	2.08	2.12	2.16	2.40	1.76
1780	2.24	2.20	2.10	2.20	1.70	2.06	2.00	1.94	1.60	1.28
1790	1.24	2.62	2.36	3.12	2.42	2.50	2.64	1.96	2.30	2.30
1800	2.56	1.90	2.30	2.02	2.50	1.64	1.38	1.80	2.32	1.50
1810	1.98	1.42	1.32	2.00	1.70	2.60	2.74	1.92	1.46	1.94
1820	2.32	2.02	1.16	1.64	1.64	2.28	2.24	2.30	2.42	2.24
1830	2.20	2.06	2.36	2.10	2.82	2.58	2.20	2.22	2.78	2.76
1840	2.54	2.08	0.90	1.32	2.12	1.58	1.92	1.20	1.14	1.74
1950	1.58	1.90	2.56	1.92	2.64	2.12	2.12	2.02	2.34	1.64
1860	1.56	1.78	1.76	1.80	1.42	1.94	2.68	2.50	3.02	2.96
1870	2.22	2.12	2.38	1.34	1.90	2.62	2.06	2.34	2.18	1.86
1880	1.02	1.22	1.96	1.82	2.50	2.14	2.40	2.62	1.98	1.68
1890	1.28	1.60	1.80	1.38	1.84	2.00	1.24	2.48	1.96	1.24
1900	1.92	2.08	1.42	2.12	0.72	2.10	2.02	2.84	2.64	1.64
1910	1.62	1.74	1.84	1.88	2.10	1.54	2.06	1.10	1.24	1.76
1920	1.64	2.28	....	....	....	....	....	....	....	....

Modern H, 17, 22, 23, 24, 25, 26 (BMH), 6 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1580	....	....	....	....	....	....	....	....	0.71	1.02
1590	0.94	1.36	1.06	1.12	1.48	2.10	1.97	2.04	2.08	2.99
1600	1.78	2.14	2.64	2.87	3.41	3.36	3.14	2.77	3.13	2.77
1610	3.48	3.56	2.70	2.59	2.67	2.67	2.48	2.30	2.39	2.68
1620	2.26	2.81	1.86	1.39	1.66	2.30	1.94	2.72	2.28	2.73
1630	1.84	1.13	1.04	1.82	2.01	2.13	2.26	2.07	1.35	1.87
1640	2.52	1.90	1.58	1.60	2.87	2.13	2.54	2.05	1.64	1.86

Modern H, 17, 22, 23, 24, 25, 26 (BMH), 6 trees—Continued

A.D.	0	1	2	3	4	5	6	7	8	9
1650	2.32	2.14	2.25	2.38	1.70	2.57	2.30	1.80	1.47	1.63
1660	1.81	2.22	1.97	1.72	1.34	1.61	1.18	1.18	1.03	1.34
1670	1.18	1.62	2.77	1.84	1.60	1.72	0.95	1.38	1.50	1.74
1680	2.06	2.05	1.38	2.08	1.41	0.18	1.31	1.92	2.36	2.18
1690	1.65	1.42	1.95	1.44	1.35	1.41	1.02	1.38	1.34	1.91
1700	1.50	2.18	1.50	1.12	1.16	1.92	1.72	0.99	1.32	1.72
1710	1.48	1.73	1.22	1.47	1.30	1.47	1.32	1.33	1.48	1.42
1720	1.79	1.59	1.54	1.78	1.60	2.10	1.87	1.31	1.45	0.75
1730	0.74	0.81	0.86	0.79	1.06	0.28	0.54	0.59	0.82	0.78
1740	0.72	0.79	0.97	1.21	1.06	1.50	1.67	1.78	0.42	1.36
1750	1.44	1.04	0.91	1.15	1.23	0.59	0.62	0.67	0.76	1.12
1760	1.01	1.27	1.48	1.48	1.68	1.24	1.63	1.64	1.40	0.97
1770	1.30	1.57	1.58	0.61	1.12	0.80	0.79	0.79	0.71	0.72
1780	0.64	0.67	0.74	0.81	1.08	0.56	0.84	0.97	0.60	0.80
1790	0.81	1.13	1.05	1.25	1.24	1.10	0.91	0.91	1.02	1.12
1800	1.35	1.06	1.28	1.05	0.88	0.91	0.77	0.77	0.66	0.75
1810	0.87	0.90	0.81	0.43	0.65	1.03	1.07	0.72	0.16	0.45
1820	0.36	0.48	0.26	0.25	0.50	0.51	0.61	0.48	0.85	0.67
1830	1.02	0.87	0.81	0.90	0.70	0.84	0.82	0.82	0.87	0.92
1840	0.88	1.00	0.71	0.85	0.76	0.76	0.69	0.07	0.66	0.87
1850	0.71	0.30	0.87	0.95	0.65	0.66	0.65	0.89	0.89	0.54
1860	0.80	0.16	0.85	0.72	0.33	0.72	0.89	0.91	1.23	1.19
1870	0.73	0.32	0.62	0.72	0.62	0.92	0.72	0.85	0.92	0.45
1880	0.68	0.76	0.57	0.65	0.76	0.93	0.68	0.87	0.84	0.72
1890	0.84	0.94	0.78	0.59	0.60	0.59	0.37	0.74	0.70	0.39
1900	0.28	0.42	0.12	0.75	0.37	0.78	0.70	1.04	1.12	1.02
1910	1.16	1.14	0.82	0.82	1.06	0.94	1.05	0.82	0.81	0.72

Modern H, 27, 28 (BML), 2 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1700	1.28	1.25	1.76	1.28	0.96	1.23	1.59	0.97	1.15	1.21
1710	1.70	1.99	1.72	1.65	1.34	1.50	1.57	1.47	1.84	2.55
1720	2.96	3.07	3.26	2.78	2.74	4.00	4.06	2.88	3.04	1.75
1730	3.75	3.26	3.20	3.55	3.39	1.26	1.99	1.94	2.67	2.02
1740	1.94	1.82	2.49	2.61	2.94	3.43	4.32	3.48	1.56	3.11
1750	2.44	1.98	1.99	1.74	2.37	1.19	1.35	1.37	1.61	2.27
1760	2.13	2.00	2.83	2.17	2.47	1.72	2.57	2.66	2.75	1.77
1770	1.84	2.79	2.85	1.28	1.82	1.50	1.37	1.11	1.37	1.13
1780	1.13	1.36	1.38	1.75	2.02	1.05	1.58	2.21	1.12	1.11
1790	1.48	1.69	1.59	2.28	1.88	1.65	1.08	1.31	1.46	1.67
1800	1.84	1.24	2.03	1.43	1.65	1.43	1.31	1.35	1.57	1.03
1810	1.33	1.66	1.41	1.07	1.49	1.85	1.72	1.52	0.64	0.94
1820	0.82	0.71	0.27	0.31	0.62	0.68	1.02	0.98	1.46	1.05
1830	1.70	1.08	1.57	1.31	1.31	1.41	1.37	1.58	1.56	1.53
1840	1.33	1.67	1.25	1.32	1.09	1.17	0.83	0.35	0.70	1.04
1850	0.75	0.39	1.07	1.12	0.91	0.94	1.05	1.22	0.92	0.66
1860	1.20	0.44	1.14	0.80	0.50	0.96	1.28	1.09	1.22	1.39
1870	1.10	0.40	0.67	0.74	0.66	1.24	0.57	1.08	1.17	0.68
1880	0.80	1.17	0.88	0.66	1.28	1.39	0.88	1.36	1.40	1.13
1890	1.43	1.29	1.15	0.90	0.81	0.71	0.51	0.98	0.84	0.41
1900	0.33	0.48	0.02	0.81	0.26	0.75	0.84	1.51	1.45	1.37
1910	1.37	1.64	1.33	1.28	1.61	1.47	1.70	0.88	....	....

Modern H, 39, 40, 41, 42 (AE), 4 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1660	....	....	2.30	1.50	1.20	2.25	0.72	0.82	0.72	0.45
1670	0.79	1.13	1.21	1.40	1.70	1.43	0.83	1.24	1.72	1.06
1680	1.81	1.72	1.31	1.67	0.85	0.17	1.80	1.68	1.23	1.87
1690	2.55	1.60	2.55	2.63	1.61	1.40	0.90	1.30	1.97	2.42
1700	1.79	2.37	1.20	1.38	0.98	1.64	2.07	1.07	1.54	1.41
1710	2.49	2.01	1.46	1.04	0.76	1.22	1.00	1.24	1.75	1.70
1720	2.30	1.78	1.30	1.67	0.97	1.30	1.90	2.04	1.66	0.29
1730	0.95	1.16	1.51	1.21	1.45	0.36	1.04	0.77	0.96	1.00
1740	0.86	0.90	0.77	1.16	0.80	1.08	1.45	1.98	0.61	1.82
1750	1.26	1.06	0.93	0.72	1.21	0.82	0.70	0.69	0.71	0.81
1760	0.73	0.73	0.96	0.93	0.99	0.66	1.50	0.85	1.26	1.10
1770	1.44	1.56	1.18	0.34	0.84	0.95	0.55	0.53	0.66	0.57
1780	0.52	0.68	0.58	0.77	0.75	0.68	0.70	0.97	0.52	0.40
1790	0.47	0.63	0.76	0.91	0.48	0.66	0.64	0.44	0.52	0.59
1800	0.62	0.31	0.86	0.60	0.62	0.43	0.24	0.66	0.59	0.62
1810	0.42	0.75	0.80	0.54	0.63	1.09	1.44	1.29	0.37	0.40
1820	0.31	1.00	0.43	0.41	0.35	0.58	0.56	0.39	0.87	0.68
1830	0.90	0.86	1.25	1.19	0.86	0.93	0.64	0.70	0.83	1.11
1840	1.12	1.01	0.84	0.76	0.54	0.59	0.69	0.04	0.76	0.66
1850	0.76	0.25	0.77	0.92	0.68	0.66	0.67	0.48	0.65	0.45
1860	0.60	0.02	0.69	0.39	0.10	0.38	0.37	0.55	0.65	0.85
1870	0.40	0.00	0.42	0.25	0.43	0.44	0.43	0.10	0.46	0.26
1880	0.26	0.29	0.27	0.25	0.38	0.21	0.39	0.52	0.59	0.44
1890	0.69	0.69	0.73	0.74	0.54	0.27	0.24	0.35	0.16	0.46
1900	0.37	1.12	0.25	0.26	0.32	0.38	0.32	0.44	0.38	0.38
1910	0.37	0.53	0.66	0.35	0.80	0.85	0.99	0.92	0.52	0.84

COAST ZONE

Boise, Idaho (BI), 10 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1650	....	....	1.70	0.65	1.50	1.65	2.05	1.05	1.70	2.05
1660	1.70	1.75	1.30	1.50	1.30	1.00	1.60	1.40	0.90	1.50
1670	1.80	1.75	1.15	1.60	0.90	1.15	0.90	0.80	0.80	1.25
1680	0.75	1.25	1.10	1.20	1.20	1.05	1.00	1.40	1.40	1.25
1690	2.00	1.75	2.15	2.45	3.55	2.35	1.95	2.45	2.15	2.15
1700	2.20	2.05	3.15	3.20	1.85	2.30	2.90	2.40	1.75	1.60
1710	2.05	1.85	1.95	1.75	1.10	0.90	1.35	0.95	1.10	1.00
1720	1.50	0.50	0.60	0.95	0.80	0.75	0.80	1.00	0.75	0.50
1730	0.50	0.85	1.20	1.05	1.00	1.20	1.00	1.45	1.60	1.00
1740	1.00	1.35	0.90	1.35	1.05	1.35	1.75	1.50	1.45	1.45
1750	1.95	2.20	2.35	1.60	1.64	2.28	1.80	1.58	2.21	2.09
1760	1.98	2.91	2.79	2.33	2.06	2.45	2.51	2.88	2.51	2.05
1770	1.98	1.98	2.28	1.12	0.81	1.28	1.65	1.81	1.32	1.42
1780	1.80	1.48	1.74	1.38	1.14	1.62	1.63	1.29	1.57	1.55
1790	1.67	1.99	2.19	1.98	1.56	1.27	1.37	1.15	0.93	1.36
1800	1.53	1.57	1.49	1.44	1.45	1.61	1.59	0.97	1.11	1.15
1810	0.60	0.70	1.02	0.98	1.18	1.10	1.12	1.00	1.15	1.15
1820	1.15	1.23	1.11	1.20	1.09	1.07	0.97	1.08	1.25	1.18
1830	1.06	0.83	1.36	1.01	0.87	1.00	1.02	1.01	1.00	0.91
1840	0.77	0.88	0.92	0.79	0.74	0.89	0.85	0.79	0.72	0.70
1850	0.82	0.79	0.71	0.68	0.99	0.83	0.67	0.93	0.88	0.64
1860	0.94	1.06	0.90	0.76	0.72	0.68	0.90	0.78	0.92	0.91
1870	0.70	0.71	0.88	0.91	0.84	0.91	0.93	0.94	0.94	0.96
1880	0.73	0.82	0.70	0.60	0.80	1.07	0.71	0.85	0.76	0.48
1890	0.45	0.69	0.78	0.53	0.63	0.72	0.64	0.36	0.59	0.62
1900	0.83	0.87	0.85	0.85	0.76	0.75	0.59	0.68	0.86	0.87
1910	0.86	0.87	0.78	0.79	0.63	0.58	0.52	0.42	0.74	0.93
1920	0.64	0.79	0.75	....	....	....	....	....	....	....

Boise, Idaho, 3 trees selected

A.D.	0	1	2	3	4	5	6	7	8	9
1650	....	....	1.70	0.65	1.50	1.65	2.05	1.05	1.70	2.05
1660	1.70	1.75	1.30	1.50	1.30	1.00	1.60	1.40	0.90	1.50
1670	1.80	1.75	1.15	1.60	0.90	1.15	0.90	0.80	0.80	1.25
1680	0.75	1.25	1.10	1.20	1.20	1.05	1.00	1.40	1.40	1.25
1690	2.00	1.75	2.15	2.45	3.55	2.35	1.95	2.45	2.15	2.15
1700	2.20	2.05	3.15	3.20	1.85	2.30	2.90	2.40	1.75	1.60
1710	2.05	1.85	1.95	1.75	1.10	0.90	1.35	0.95	1.10	1.00
1720	1.50	0.50	0.60	0.95	0.80	0.75	0.80	1.00	0.75	0.50
1730	0.50	0.85	1.20	1.05	1.00	1.20	1.00	1.45	1.60	1.00
1740	1.00	1.35	0.90	1.35	1.05	1.35	1.75	1.50	1.45	1.45
1750	1.95	2.20	2.35	1.60	1.64	2.28	1.80	1.58	2.22	2.09
1760	1.98	2.91	2.79	2.33	2.06	2.45	2.51	2.82	2.51	2.05
1770	1.98	1.98	2.28	2.15	0.84	1.32	1.71	1.88	1.37	1.49
1780	1.89	1.50	1.80	1.63	1.12	1.88	1.80	1.39	1.53	1.65
1790	1.23	2.45	2.45	2.36	1.89	1.49	1.72	1.45	1.15	1.63
1800	1.74	1.55	1.63	1.72	2.01	1.96	2.05	1.20	0.93	0.83
1810	0.25	0.33	0.59	0.68	1.10	1.18	1.26	1.23	1.41	1.41
1820	1.28	1.45	1.78	1.33	1.36	1.42	1.56	1.45	1.70	1.80
1830	1.42	0.90	1.82	1.78	1.12	1.10	1.20	1.25	1.48	1.18
1840	0.92	1.25	1.25	0.95	0.75	0.78	0.78	0.35	0.48	0.58
1850	0.65	0.68	0.42	0.82	1.08	0.81	0.75	0.93	0.82	0.63
1860	0.88	0.95	0.94	0.92	0.81	0.77	1.03	1.03	1.11	1.09
1870	0.81	0.78	0.82	0.91	1.15	1.14	1.03	1.16	1.17	1.12
1880	1.05	0.93	0.73	0.60	0.73	1.07	0.87	0.92	0.91	0.42
1890	0.41	0.65	0.72	0.40	0.53	0.55	0.39	0.16	0.45	0.40
1900	0.36	0.49	0.62	0.41	0.63	0.61	0.49	0.55	0.85	0.80
1910	0.68	0.85	0.46	0.62	0.58	0.59	0.50	0.31	0.66	0.90
1920	0.65	0.41	0.55	....	....	....	....	....	....	....

Baker, Oregon (BO), 7 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1660	1.60	1.65	0.55	1.10	1.25	1.10	2.00	2.40	2.00	2.10
1670	2.85	3.35	2.70	2.20	2.20	1.90	1.45	1.25	1.80	1.65
1680	0.90	1.00	1.00	0.90	1.25	1.35	1.60	1.25	1.35	1.60
1690	1.35	1.45	1.45	1.00	1.50	1.20	1.20	1.45	1.05	0.80
1700	0.75	0.60	0.80	1.00	0.95	1.30	1.80	1.65	1.50	1.70
1710	2.80	3.20	2.95	2.40	1.75	2.70	2.40	1.50	1.65	1.00
1720	1.25	0.90	1.10	1.10	1.10	1.65	2.10	2.20	1.45	1.55
1730	1.90	1.60	1.75	1.75	1.25	1.70	1.50	2.10	1.60	1.20
1740	1.25	1.35	1.05	1.05	1.25	1.45	1.25	1.10	1.10	1.30
1750	1.35	1.20	1.30	0.85	0.85	0.80	0.50	0.65	0.65	0.45
1760	1.15	1.20	0.80	0.75	0.74	0.64	0.90	0.82	0.78	0.78
1770	0.88	0.97	1.02	0.98	1.06	0.90	0.75	0.64	0.85	0.95
1780	1.10	0.84	0.86	0.78	0.66	0.47	0.79	0.72	0.86	1.04
1790	1.13	1.74	1.92	1.55	1.70	1.50	1.79	1.02	1.32	1.29
1800	1.18	1.16	1.14	1.14	0.91	1.03	0.90	0.82	0.89	1.11
1810	1.04	1.04	1.64	1.42	1.66	1.23	1.24	1.09	1.22	1.64
1820	1.17	1.23	1.65	0.87	1.58	1.84	1.53	0.89	1.08	0.93
1830	0.87	1.18	1.15	1.05	0.89	0.89	1.21	1.38	1.67	1.69
1840	1.14	1.11	0.83	0.70	0.77	1.12	0.94	0.59	0.84	0.78
1850	0.57	0.81	0.77	0.87	0.88	1.23	0.97	1.16	1.23	1.00
1860	1.00	1.19	1.06	1.12	1.18	1.29	1.87	1.39	1.66	1.32
1870	1.28	1.20	1.26	1.52	1.29	1.35	1.79	2.03	1.89	1.71
1880	1.39	1.72	1.29	0.98	1.08	1.44	1.05	1.05	1.18	0.87
1890	0.75	1.02	0.85	0.72	1.16	0.95	1.01	1.16	1.21	0.80
1900	1.23	1.09	0.99 +	1.06	1.17	1.02	0.91	1.10	0.93	0.94
1910	0.76	0.69	0.81	1.05	0.78	0.82	0.95	0.60	0.65	0.71
1920	0.61	0.76	0.32	0.60	0.52	....	....	....	....	....

The Dalles, Oregon (DL), 3 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1760	....	....	....	....	....	3.00	3.30	3.50	1.94	2.72
1770	1.55	1.93	2.23	1.72	1.68	1.57	0.87	0.92	0.93	1.10
1780	0.75	0.98	1.30	1.18	0.99	0.90	1.64	1.01	0.82	0.88
1790	0.97	0.81	1.20	1.18	0.84	0.60	0.49	0.58	1.10	1.18
1800	1.11	1.12	1.25	0.93	0.79	1.10	1.25	1.26	1.68	1.43
1810	1.39	1.39	1.56	1.81	1.45	1.35	1.18	1.15	0.80	1.28
1820	1.21	1.05	0.93	0.81	0.82	0.84	0.99	1.25	0.88	1.15
1830	1.25	1.08	1.00	1.35	1.12	1.21	1.00	0.88	0.99	0.67
1840	0.68	0.44	0.66	0.92	0.74	1.02	0.98	0.54	0.48	0.34
1850	0.63	0.42	0.65	0.69	0.94	0.88	0.96	1.02	1.05	1.05
1860	1.21	1.08	1.09	1.17	1.63	1.06	1.23	1.12	1.07	1.07
1870	1.30	1.23	1.39	1.09	1.18	0.74	1.24	1.11	1.03	1.01
1880	1.16	1.00	1.34	1.12	1.23	1.16	1.19	1.01	0.77	0.68
1890	0.55	0.37	0.38	0.39	0.54	0.73	0.95	1.38	1.21	1.03
1900	1.14	1.13	0.85	1.09	1.13	0.79	0.85	0.82	1.14	0.79
1910	0.66	0.70	0.83	0.97	0.85	0.91	0.89	0.92	0.74	0.70
1920	0.68	1.12	0.89	0.68	1.05	....	....	....	....	....

Oregon Coast (OC)

(See Volume I, Appendix, page 117)

Klamath Falls, Oregon (KF), 12 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1790	....	....	1.01	1.17	0.83	0.69	0.75	1.16	1.25	1.74
1800	1.02	1.05	1.32	1.23	1.12	1.23	1.44	1.18	1.15	1.35
1810	1.14	1.18	0.94	1.93	0.94	0.86	0.91	0.96	1.16	1.15
1820	0.93	0.95	0.81	0.83	0.56	0.92	0.91	0.86	0.94	0.61
1830	1.05	1.08	1.47	0.87	0.91	1.47	1.64	1.51	1.43	0.48
1840	1.08	0.57	0.73	0.63	0.35	0.76	0.50	0.69	0.81	0.72
1850	0.91	0.97	0.84	1.21	0.94	1.00	0.85	0.94	0.79	0.69
1860	1.10	1.35	0.99	0.99	0.98	0.84	1.01	1.03	1.09	0.42
1870	0.72	0.54	0.66	0.85	0.91	0.80	1.08	1.05	1.15	0.98
1880	0.85	1.12	0.81	0.93	1.13	1.04	0.96	1.04	0.99	0.32
1890	0.69	0.79	0.85	1.14	1.56	1.12	1.12	1.21	0.35	0.79
1900	0.92	1.04	0.99	1.20	1.19	0.92	0.95	1.12	1.00	1.19
1910	1.19	0.94	1.08	1.33	1.23	0.77	1.18	0.86	0.50	0.76
1920	0.31	0.61	0.51	0.75	....	....	....	....	....	....

Meadow Valley Pines, Plumas County, California (CP), 9 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1550	....	2.13	1.95	1.80	1.98	2.91	2.37	1.80	1.50	1.17
1560	1.26	1.47	1.62	1.77	1.68	1.92	1.11	0.93	1.26	1.20
1570	0.90	1.59	1.32	1.26	1.53	1.68	2.19	1.29	1.38	0.93
1580	1.02	1.05	1.23	1.35	1.17	1.23	1.26	1.23	0.75	0.36
1590	0.90	1.05	0.90	0.42	0.24	0.51	0.75	0.90	0.90	0.87
1600	1.17	1.11	1.50	0.99	0.75	1.20	1.23	1.20	1.05	1.08
1610	1.80	1.44	0.96	1.50	1.53	1.20	1.50	1.83	1.44	1.80
1620	1.95	1.35	1.53	2.40	1.80	1.74	1.50	2.76	1.80	2.31
1630	2.19	1.80	2.01	2.46	3.66	3.51	3.54	4.50	3.03	2.64
1640	2.88	3.60	3.09	3.84	4.02	2.91	3.84	3.39	2.55	3.21
1650	3.24	3.69	2.70	2.67	2.76	3.66	3.42	2.94	3.12	3.63
1660	2.43	3.30	3.30	2.40	3.30	2.79	3.15	3.51	2.94	3.27

Meadow Valley Pines (CP), 9 trees—Continued

A.D.	0	1	2	3	4	5	6	7	8	9
1670	2.88	2.67	3.00	3.72	3.42	3.48	2.88	2.97	3.09	3.24
1680	3.12	3.75	3.39	2.82	3.27	3.57	3.39	2.94	3.18	2.16
1690	2.52	3.48	3.18	2.58	3.78	2.97	2.79	2.79	2.73	3.12
1700	3.12	2.16	2.64	2.88	2.97	2.97	2.73	2.97	3.03	2.67
1710	3.21	2.22	2.67	2.49	2.85	3.30	3.75	3.54	3.21	2.82
1720	3.24	2.85	3.18	3.03	2.46	2.61	3.21	2.85	2.61	2.82
1730	3.12	3.03	2.88	2.49	2.67	2.82	3.12	2.61	3.21	2.97
1740	2.58	2.61	2.61	3.06	2.70	2.64	2.43	2.76	2.37	2.85
1750	2.82	2.85	2.52	2.64	3.03	3.15	2.49	2.58	2.76	3.12
1760	2.37	2.97	2.55	2.10	2.25	2.64	2.49	2.37	2.46	2.13
1770	2.52	2.28	2.46	2.70	2.85	2.97	2.49	2.07	2.67	2.64
1780	3.30	2.73	2.70	2.97	2.73	2.97	3.18	2.37	2.70	2.43
1790	2.52	2.91	3.42	3.33	3.06	2.91	2.31	2.70	3.63	3.39
1800	3.66	3.33	2.91	3.30	3.78	3.63	3.57	3.72	4.11	4.56
1810	4.74	4.44	4.92	3.99	4.17	3.30	3.51	3.21	3.57	3.57
1820	3.33	2.49	2.58	1.68	1.89	2.37	2.76	2.70	2.43	2.91
1830	1.95	2.13	2.91	2.46	2.25	2.46	2.40	2.82	2.37	2.31
1840	2.85	3.09	2.70	3.06	2.82	3.63	3.51	2.94	2.25	1.83
1850	2.19	2.58	2.67	2.43	2.43	3.00	2.58	2.61	2.19	2.16
1860	2.70	2.61	2.10	2.34	2.19	2.25	2.49	3.18	2.82	3.18
1870	3.39	3.36	3.48	3.27	2.70	2.79	2.34	2.73	2.43	2.58
1880	2.01	2.70	1.71	1.68	1.95	2.31	1.59	1.79	1.83	1.65
1890	1.59	1.89	1.89	2.10	2.31	1.83	2.04	1.98	1.77	1.92
1900	2.67	2.10	2.13	2.16	2.01	2.07	2.07	2.19	2.16	1.98
1910	1.59	1.77	2.28	2.22	2.07	1.77	1.74	1.62	1.65	1.68
1920	1.59	1.92	....	....	....	....	....	....	....	....

Calaveras Pines (CVP), 14 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1620	....	1.60	1.70	1.40	1.30	1.15	1.95	1.35	1.40	1.65
1630	1.55	0.90	1.15	1.40	1.45	1.55	1.90	2.45	2.10	1.45
1640	1.20	1.40	1.45	1.75	1.80	1.80	1.80	2.20	1.90	1.45
1650	1.95	1.50	1.50	0.60	1.65	0.70	1.60	1.05	0.90	1.15
1660	1.85	1.50	1.70	2.05	1.15	1.10	1.75	1.80	0.95	1.88
1670	1.93	1.83	1.65	2.15	1.70	1.83	1.58	1.88	1.88	1.65
1680	1.60	2.90	2.08	1.35	2.00	2.75	1.95	1.65	2.03	1.40
1690	1.48	1.95	1.35	1.53	2.25	2.20	1.88	1.55	1.50	2.52
1700	1.95	1.20	1.32	2.41	2.00	2.90	2.48	2.00	2.12	2.58
1710	2.81	1.89	2.78	2.31	2.57	2.14	2.05	2.04	1.70	1.59
1720	1.85	1.85	1.67	2.32	2.11	1.68	2.30	2.10	1.56	1.12
1730	1.62	1.65	1.56	1.36	1.42	1.20	1.78	1.28	1.56	1.69
1740	1.59	2.21	1.71	1.26	1.46	1.34	1.55	1.63	1.31	1.86
1750	1.97	1.91	1.75	1.74	1.26	1.74	1.35	1.15	1.83	1.88
1760	1.60	2.14	1.73	1.14	1.32	1.42	1.84	1.31	1.77	1.54
1770	2.24	1.69	2.14	2.06	1.81	1.77	1.46	1.05	1.14	1.18
1780	1.16	0.95	1.24	1.12	1.30	1.69	1.39	1.03	1.53	1.26
1790	1.24	1.59	2.15	1.74	1.41	1.33	1.33	1.35	1.28	1.30
1800	1.32	0.92	1.17	1.18	1.29	1.40	1.28	1.26	1.43	1.44
1810	1.48	1.54	1.60	1.89	2.02	1.74	1.87	1.41	1.66	1.48
1820	1.52	1.47	1.44	1.29	1.22	1.61	1.62	1.61	1.72	1.76
1830	1.84	1.96	2.46	1.99	1.23	1.49	1.53	1.34	1.64	1.54
1840	1.95	1.59	1.82	1.48	1.32	2.16	1.65	1.73	1.57	1.20
1850	1.36	1.49	1.45	1.82	1.67	2.18	1.67	1.48	1.45	1.17
1860	2.39	1.87	1.45	1.40	1.79	1.26	1.42	1.28	1.79	1.98
1870	2.86	2.24	2.36	2.60	1.59	2.33	1.90	2.01	2.26	2.22
1880	1.78	2.08	1.66	1.75	2.24	2.32	1.67	1.50	1.47	1.62
1890	1.48	1.70	1.82	1.97	2.18	1.91	1.81	1.71	1.69	1.74
1900	2.28	1.65	1.60	1.77	1.48	1.70	1.61	1.62	1.37	1.02
1910	1.22	1.03	1.22	1.42	1.50	1.26	1.06	0.84	0.80	1.03
1920	1.07	1.12	0.95	1.18	0.57	....	....	....	....	....

Big Creek, California (BC), 5 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1700	....	....	....	0.80	0.60	1.08	0.58	0.70	0.73	0.60
1710	1.12	1.05	1.12	1.00	1.18	0.93	1.18	1.38	2.40	2.10
1720	2.22	1.53	1.66	1.89	1.56	1.85	1.97	1.82	1.45	0.96
1730	1.84	2.11	2.15	1.59	1.94	1.71	1.95	1.89	3.18	2.60
1740	3.56	3.05	3.22	2.94	3.19	3.42	4.08	3.62	3.24	2.84
1750	2.86	2.81	2.43	2.18	2.48	2.11	1.81	1.90	1.86	2.41
1760	2.62	2.72	2.06	2.27	1.89	2.10	2.68	1.82	2.26	2.87
1770	2.62	3.28	2.36	3.13	2.70	1.88	1.63	1.13	1.71	1.70
1780	1.96	2.06	1.70	1.32	2.57	2.55	1.84	1.93	1.52	2.39
1790	2.71	2.12	2.29	2.22	1.59	1.13	1.68	2.05	1.76	2.17
1800	1.98	2.38	2.36	2.20	2.24	1.97	2.18	2.62	2.16	2.04
1810	2.95	2.44	1.77	2.47	2.32	2.53	2.45	2.06	1.92	1.92
1820	1.79	1.66	1.63	1.77	1.58	2.16	1.89	1.78	2.02	1.23
1830	2.28	2.00	1.75	1.91	1.65	1.78	2.25	1.42	1.64	1.68
1840	1.84	1.26	1.45	1.22	0.87	1.67	1.22	1.14	1.17	1.06
1850	1.39	1.41	1.44	2.00	1.61	1.59	1.78	1.52	1.32	1.54
1860	2.03	1.56	1.28	1.13	0.78	1.35	1.29	1.24	1.70	1.55
1870	1.54	1.64	2.52	1.62	1.46	1.83	1.46	1.26	1.87	1.19
1880	1.08	1.17	0.83	0.80	1.53	1.14	0.98	1.00	1.06	0.99
1890	1.38	1.27	1.04	1.34	1.36	1.55	1.43	1.70	1.15	1.23
1900	1.28	1.52	0.93	1.11	0.99	1.37	1.21	1.42	1.14	1.28
1910	1.46	0.93	0.72	0.93	1.38	1.03	1.04	0.98	1.03	1.09

Springville Pines (EP), 8 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1720	0.70	0.62	0.90	1.18	0.65	0.72	0.78	0.90	0.65	0.51
1730	0.68	0.50	0.70	0.85	0.62	0.65	0.70	0.55	1.00	0.68
1740	0.62	0.92	0.82	0.62	0.78	1.05	0.70	0.92	0.92	0.85
1750	1.12	0.85	0.85	1.00	0.65	0.51	0.65	0.72	1.08	0.85
1760	0.78	1.25	0.92	1.15	1.05	0.92	1.33	1.22	1.40	0.73
1770	0.92	1.12	1.21	1.52	1.52	1.50	1.29	0.60	0.78	0.92
1780	1.01	0.73	0.96	0.51	0.62	0.92	0.94	0.91	0.74	0.89
1790	0.97	1.31	1.35	1.12	1.25	0.73	0.64	0.93	0.94	0.84
1800	1.08	1.07	1.15	1.51	1.36	1.37	1.16	1.17	0.89	0.94
1810	0.92	1.15	0.70	0.97	0.93	1.02	1.18	0.87	1.28	1.20
1820	0.90	1.09	0.65	0.64	0.63	1.02	1.24	0.98	1.28	0.94
1830	0.98	1.21	1.27	0.87	0.64	0.79	0.84	0.80	1.01	1.11
1840	1.22	0.62	0.88	0.67	0.61	0.90	0.54	0.49	0.54	0.67
1850	1.04	1.07	1.23	1.37	1.06	1.59	1.14	1.06	0.57	0.64
1860	1.03	0.95	0.79	1.02	0.52	0.81	1.05	0.97	1.25	1.43
1870	1.07	1.18	1.35	1.04	0.93	1.13	0.86	0.91	1.11	0.98
1880	0.66	0.97	0.91	1.02	1.07	1.79	1.42	1.04	1.07	0.80
1890	0.74	0.92	0.87	1.08	1.18	1.28	1.02	1.19	0.89	0.85
1900	1.04	0.89	0.90	1.16	0.94	0.88	1.01	1.16	1.09	1.32
1910	1.14	0.84	0.74	0.78	0.85	0.77	0.91	0.85	0.66	0.71
1920	0.73	0.72	0.69	0.88	0.56	....	....	....	....	....

Mount Wilson, California (W), 8 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1720	....	....	....	....	....	10.40	11.00	9.10	9.10	5.90
1730	6.00	8.90	6.30	8.10	7.10	5.90	6.35	7.00	5.80	6.10
1740	6.70	7.90	7.75	6.60	5.85	8.95	7.05	8.45	7.60	8.90
1750	4.75	5.15	6.80	4.20	3.30	6.10	4.55	5.85	6.25	5.15
1760	6.30	7.60	5.85	7.30	9.35	5.85	8.70	7.25	8.55	6.61
1770	7.10	7.23	5.52	6.20	6.25	5.62	5.12	4.57	5.40	5.50

Mount Wilson, California (W), 8 trees—Continued

A.D.	0	1	2	3	4	5	6	7	8	9
1780	6.13	7.00	5.37	5.30	7.00	6.70	4.30	5.12	4.65	5.22
1790	5.32	4.90	6.45	5.97	4.45	2.88	2.77	4.60	3.77	5.47
1800	5.60	5.77	7.15	6.12	8.50	7.65	5.85	4.67	7.05	6.05
1810	5.75	6.15	4.56	4.72	4.42	5.49	5.34	4.81	6.86	5.40
1820	6.25	5.08	5.00	4.11	3.93	4.83	5.83	5.10	5.43	5.16
1830	4.86	4.63	5.98	4.26	3.85	4.41	4.00	4.96	4.91	5.26
1840	5.71	3.70	4.51	3.16	3.61	3.97	4.13	4.13	3.37	3.80
1850	4.55	4.45	4.70	5.06	4.99	6.50	2.79	2.81	3.46	4.82
1860	5.26	4.71	5.66	5.26	3.42	4.15	4.67	4.32	5.92	5.75
1870	6.21	5.01	5.46	5.49	5.12	5.70	4.86	4.01	4.93	4.42
1880	3.05	4.52	3.87	4.31	4.17	4.67	4.042	4.25	3.57	3.48
1890	4.89	5.11	4.62	4.63	4.18	4.27	3.85	3.60	3.96	2.77
1900	5.22	4.91	3.75	3.89	3.72	4.47	5.18	4.68	5.63	3.51
1910	3.38	3.17	3.93	3.85	3.91	4.25	4.45	4.81	3.76	4.47
1920	4.45	5.16	4.75	4.90	3.27	3.03	....	....	....	....

San Bernardino (SB), 6 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1810	....	....	....	....	....	....	....	....	....	1.88
1820	1.39	0.90	1.24	1.72	1.38	2.03	2.16	1.81	1.54	1.98
1830	1.74	1.54	1.51	1.50	1.02	1.41	1.36	1.19	1.17	1.25
1840	1.06	0.77	0.85	0.92	0.98	1.20	1.67	1.56	1.31	0.92
1850	1.10	1.27	1.30	1.88	1.22	1.67	1.08	0.94	1.15	1.14
1860	0.88	1.02	0.87	1.00	0.82	0.79	1.18	1.16	1.15	1.06
1870	1.06	1.23	1.66	1.60	1.77	1.66	1.22	1.09	1.17−	0.93
1880	0.65	0.93	0.73	0.89	0.77	1.03	0.75	0.65	0.73	0.86
1890	0.85 +	0.97	0.92	0.95	0.98	1.13	1.09	1.11	1.22	1.03
1900	1.42	1.41	1.07	0.91	1.03	0.76 +	0.88	0.89−	0.89	0.79
1910	0.74	0.71	0.88	0.92	1.03	0.76	1.07	0.86	0.80	0.83
1920	0.94	1.11	....	....	....	....	....	....	....	....

Charleston, Nevada (CH), 8 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1700	2.70	1.78	2.43	1.03	2.18	1.78	1.73	1.03	1.47	1.40
1710	0.95	1.13	1.22	0.82	1.12	1.07	0.61	0.83	1.00	1.08
1720	1.72	1.33	0.92	1.84	1.36	1.52	1.94	1.65	1.83	0.61
1730	1.54	1.26	1.44	1.41	1.38	1.12	0.63	1.00	1.51	1.05
1740	1.19	1.21	1.41	1.69	1.86	1.55	2.23	2.09	1.37	1.53
1750	2.00	1.54	1.23	0.77	0.72	0.73	0.99	1.09	1.37	1.73
1760	1.78	2.27	1.63	1.34	1.39	0.59	1.63	1.64	1.80	1.26
1770	1.39	1.55	1.77	1.35	2.28	1.82	1.90	1.27	1.09	1.19
1780	1.60	1.59	0.77	1.10	1.80	0.84	1.25	1.06	0.65	1.04
1790	1.02	1.14	1.59	2.10	1.66	0.36	0.64	1.15	0.97	1.52
1800	1.10	1.08	1.27	1.12	1.25	1.02	1.46	0.72	1.05	0.56
1810	0.69	1.09	1.20	0.51	0.82	0.79	1.06	1.06	2.13	2.43
1820	2.59	2.42	1.27	0.93	1.49	1.52	1.92	1.34	1.87	1.32
1830	1.57	1.58	1.88	1.55	1.42	1.43	0.65	1.66	1.57	1.90
1840	1.59	0.75	1.08	1.21	1.04	0.99	1.32	0.86	1.34	1.17
1850	1.29	1.04	1.42	1.76	1.84	1.70	0.78	0.26	0.79	0.88
1860	1.03	1.33	1.60	1.35	0.89	1.37	1.90	1.94	2.15	1.66
1870	2.18	1.76	1.38	1.66	2.08	2.11	1.88	1.59	1.67	0.95
1880	1.02	1.06	1.03	0.92	0.97	1.27	0.87	1.44	1.28	1.46
1890	1.49	1.78	1.86	1.86	2.11	1.72	1.13	1.54	1.24	0.53
1900	0.77	1.11	0.98	1.07	1.40	1.33	1.69	1.63	1.97	1.83
1910	1.62	1.53	1.55	1.59	1.67	1.37	1.63	1.61	2.20	1.74
1920	2.05	2.40	2.47	2.60	....	....	....	....	....	....

Pine Valley, California (PV), 4 trees

A.D.	0	1	2	3	4	5	6	7	8	9
1730	....	....	....	....	....	....	1.65	1.33	1.25	1.02
1740	1.33	1.11	0.67	1.34	1.29	0.87	0.71	0.43	0.53	0.25
1750	0.47	0.52	0.61	0.55	0.88	0.93	1.10	1.69	3.36	3.36
1760	4.20	3.67	2.86	2.30	2.32	1.40	3.44	3.60	3.50	2.56
1770	1.90	2.93	2.45	1.90	3.14	2.39	2.20	1.56	1.39	1.19
1780	1.06	1.49	0.58	1.40	2.19	1.52	2.75	2.82	1.84	1.65
1790	1.26	1.07	0.60	1.89	1.86	1.68	1.52	1.33	1.00	1.22
1800	1.25	1.46	2.16	1.90	1.50	1.97	1.29	1.21	1.67	1.16
1810	1.31	1.65	1.42	1.36	2.28	2.40	2.58	2.57	2.24	2.77
1820	0.95	1.30	0.85	0.55	0.62	1.10	1.46	1.16	2.10	0.64
1830	0.83	1.32	1.25	1.91	1.23	1.28	1.25	1.28	1.31	1.40
1840	1.25	0.81	1.39	0.55	0.65	0.51	0.99	0.85	1.18	1.15
1850	1.18	0.90	1.56	1.99	1.09	1.47	0.73	0.63	0.75	0.82
1860	0.95	1.09	1.39	1.22	0.88	1.27	1.23	0.92	1.41	1.48
1870	0.72	0.91	1.06	0.37	0.64	0.65	0.68	0.49	1.27	0.46
1880	1.19	1.16	0.61	0.59	0.90	1.20	1.27	1.29	2.04	1.63
1890	1.12	1.52	1.39	1.25	1.07	0.95	1.06	1.27	1.00	0.57
1900	0.67	0.84	0.53	0.41	0.21	0.64	0.64	0.59	0.72	0.89
1910	0.98	0.92	0.66	0.81	0.69	0.84	1.11	1.18	1.05	1.21
1920	1.38	0.93	1.28	....	....	....	....	....	....	....

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CLIMATIC CYCLES AND TREE GROWTH

VOLUME III

A STUDY OF CYCLES

BY

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FOREWORD

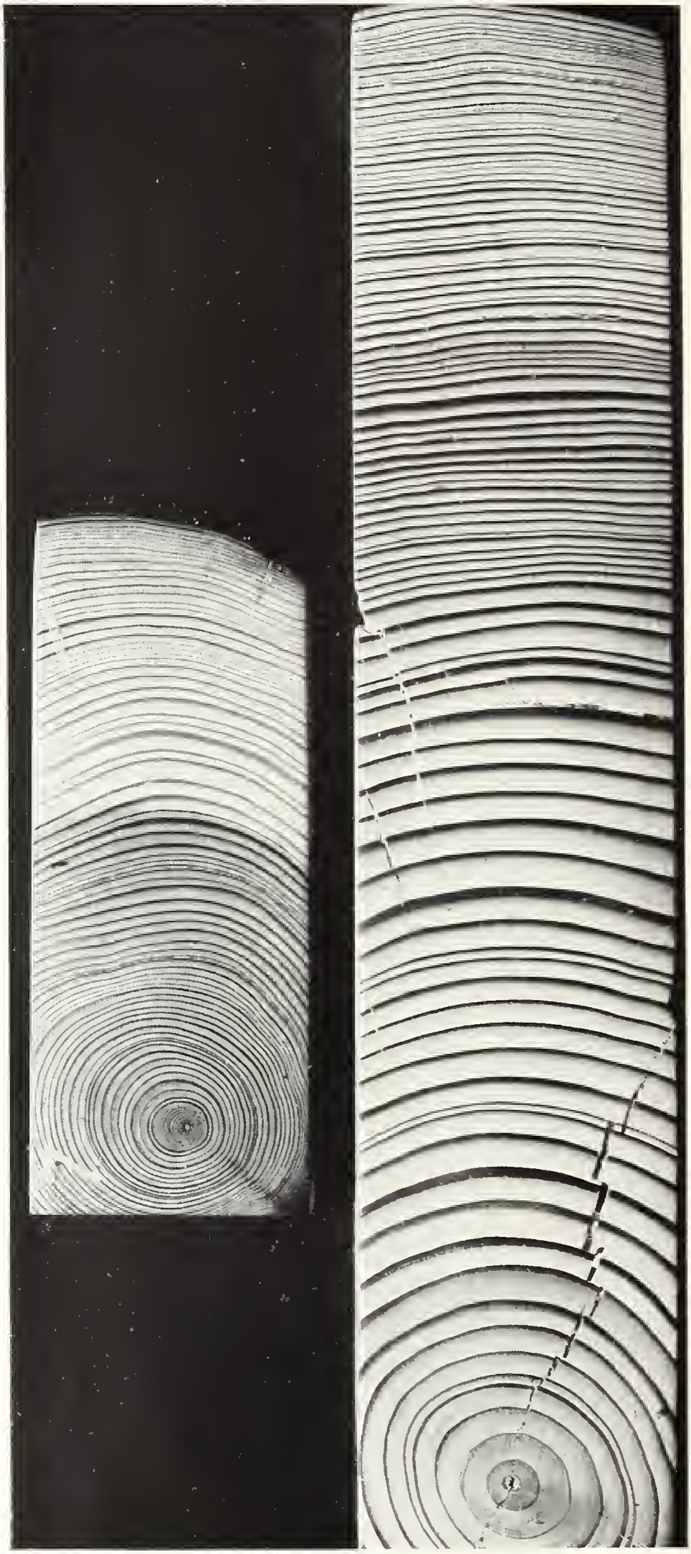
The study of cycles, like playing with empirical relations between numbers, may well have intrigued men from very early times. How else should we have been led in Asia and in America to our calendars? In celestial mechanics the cycles are exceedingly regular, but there are phenomena whether celestial, terrestrial or human in which it is obvious that there are oscillations, but in which it is also obvious that the oscillations are not regular. Such phenomena raise serious questions for the mathematician; it isn't even known whether Schuster's periodogram analysis, which is the method most perfected mathematically, is really suitable for exploring the series of oscillations. The phenomena also offer perplexing challenges to the scientist: Are they, like Brownian movements, to be regarded as fortuitous? Is there a relation between them and other cyclic phenomena which will permit us to describe, at least in part, the ones in terms of the others? And if this be true, what is the real explanation of the correlations which have been discovered? Finally, is there any possibility of prediction or of control of one phenomenon by observation or by manipulation of another?

Professor Douglass has for long been a worker in the field of cycle analysis. More than fifteen years ago he described an optical instrument and method for performing with considerable precision and with extreme rapidity a type of cycle analysis. His method seems to have been used little, if at all, by other workers. This neglect of a new tool for analysis is regrettable. Science advances by its techniques as well as by its findings of fact or its formulations of theory. Moreover, science is not a collection of personal opinion or of individual performance, it is a collaboration toward a consensus; until others have found out how the cyclograph performs for them we have not the basis for a consensus as to its merits—we have merely our faith in Douglass, and however much he may appreciate this, he would appreciate yet more a demonstration of the justification for that faith.

The collection of an enormous amount of material on tree-rings, the development of methods of cross-dating and the establishment thereby of a system of chronology represent a continued effort toward a knowledge of our past. The correlations of tree-rings with solar and terrestrial data and the intercorrelations of these not only illuminate the past, they offer hope of some future and greater success in forecasting phenomena of scientific importance and, perchance, of immediate significance to man.

So much of the work on cycles which has been done in the past and published with high hope has been found wanting by subsequent investigators, that the scientific world has today a somewhat justifiable scepticism of the validity of similar new work. The author and the Carnegie Institution offer this data and these findings to the critical examination of others to ascertain in how far they may become established in that general consensus which is science and afford a basis for further advances into the mathematical difficulties of cycle analysis, into the perplexing problems of scientific induction therefrom and into those fields of science in which the realization of our present hopes seems bound up with a fuller comprehension and utilization of these methods.

E. B. Wilson



Cross-identification of MLK-179, above, and MLK-127, below. See Plate 8.

CLIMATIC CYCLES AND TREE GROWTH

A STUDY OF CYCLES

I. INTRODUCTION

While seeking information regarding climatic influence on tree-ring growth, we have developed an improved method of studying and expressing certain climatic changes that have been disappointing to students of cycles. The chief purposes of the present writing are to describe and discuss this method of cycle analysis, to place on record the results obtained on ring growth in favorable regions, to outline the similarities over certain geographical areas, to present the resemblance of climatic cycles to certain solar cycles, and to begin the study of their use in long-range weather prediction.

The present work is based on a view sustained by recent advance, namely, that having developed an appropriate method, we should specialize upon those climatic changes which seem to occur in non-permanent but still obviously cyclic form. It is hoped that this treatment will receive consideration in connection with problems of reclamation and hydraulic engineering as well as in climatology. Although this volume is the third[1] in a series begun in 1919, a large mass of basic material still remains unpublished. It is hoped that it will be made available in the near future.

Since presentation of the material involves the facts obtained in the measurement of rings of trees, especially the western yellow pine and Douglas fir of Arizona, certain formal tests upon our ring records, such as the uniformity of ring records within a tree, the uniformity over local areas, and the like will be referred to. In other respects, without undue repetition, we desire to bring the basic material up to date. We believe that this should be investigated in the district and upon the trees with which we have worked, thus avoiding misleading results that have been found in distant localities and other environments and different biological material.

In presenting a new description of the analytical method used now for a score of years, we shall endeavor to make clear to those familiar with harmonic analysis that the new method is simply a way of finding and expressing the facts of climatic change in a more detailed and useful form. The use of the word "accidental" will be avoided as far as possible in regard to climatic changes because that word begs the question by implying uselessness to human welfare. We believe that some of the results will prove useful. From the viewpoint of climatology, our investigation is a study of the geographical extension of certain climatic similarities, because in this type of expression (the cyclogram method) similarities not hitherto observed can be recognized.

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[1] References in this book to the preceding volumes are sometimes indicated by I and II.

The Region, Climate, and Trees—Tree-ring data may extend in two ways: Geographically about the earth, and chronologically in past time. In the studies contained in this book a limited geographical area is used, commonly known as the Pueblo area. It consists largely of the Colorado Plateau in northern Arizona, northern New Mexico, and adjacent parts of Colorado and Utah, an extensive area where climatic variations are essentially similar. The Colorado Plateau is not flat like a table but is composed of wide-spread minor variations culminating at the west in the San Francisco Peaks near Flagstaff; thence toward the east it slopes down to the Little Colorado River bottom; rises again to the Chuska and Lukachukai Mountains between Arizona and New Mexico; descends thence to irregular lands extending across the Chaco areas, and rises to Mount Taylor and the Jemez Mountains at the west wall of the Rio Grande Valley in New Mexico. This area described has become especially adapted to our purpose, because in altitude it extends a thousand feet or more above and a thousand feet below the forest-border level. Rainfall is locally dependent upon altitude, and hence at the higher points forests thrive, while at the lower points the desert prevails. We thus have the forest borders and forest areas scattered through the region under consideration and we can find similar border conditions 400 miles apart without important differences in climate.

The area above described as a climatic unit has two well-defined rainy seasons per year, one in winter and one in summer. The winter rainy season has the characteristics of the temperate zone in type and movements of storms; clouds cover large areas hundreds of miles in extent and precipitation changes from year to year are much alike over a large extent of country. Rainfall is, of course, influenced by altitude and by north and south mountain ranges. The winter storms come from the west and the precipitation is greater on westerly slopes than on easterly. The spring season is exceedingly dry and rain in May and June indicates an exceptional year. The autumn is also marked by diminished rain, but is not so dry as the spring. The summer rains are tropical in their nature and come in July and August, sometimes extending into September. They are largely localized thunderstorms which are very impressive to the beholder and sometimes dangerous in the swollen washes that follow a downpour. However, their contribution to the water supply in reservoirs is small in comparison with that of winter rains.[1] They do, of course, aid the crops and the feed for cattle on the ranges. Summer rains come on southerly winds and are stirred into thunderstorm activity by the interference of mountains and by local convection. In the summer rainy season the mornings are usually clear and subject to enormous evaporation from irrigated or moistened areas.

In this area the western yellow pine (*Pinus ponderosa*—now called ponderosa pine by foresters) follows a contour zone cutting across mountains and table lands between approximate altitudes of 5000 and 8500 feet where it is

---

[1] Glenton Sykes, *Range Studies for Southwestern Range and Forest Experiment Station, Tucson, Arizona.*

Pine forest, Northern Arizona: San Francisco Peaks, Flagstaff (1904). Agassiz summit on left, 12,360 feet elevation; looking northwest from point one mile north of Flagstaff at elevation 7000 feet.

Pine (Ponderosa) forest, Northern Arizona. Courtesy, U. S. Forest Service.

governed by the moisture supply. Its altitude is generally lower on the western sides of the mountains which receive the heavier rainfall and higher on the dry eastern sides. The difference is a thousand feet in some cases.

A zone of Douglas fir (*Pseudotsuga taxifolia*) lies above the pine zone. The usefulness of the Douglas fir ring record equals that of the pine, especially in trees that grow in the transitional area along its lower edge where it mingles with the pine. Firs extend downward in favorable canyons and shady slopes almost as far as the yellow pine, and their ring records are superb in such places. Mingling with the yellow pine at the lower edges of its zone is a hard pine, the pinyon (*Pinus edulis*), a tree adapted to a water supply less than that required by the yellow pine.

Below the pine and pinyon on the mountain slopes there stand the junipers, the last outposts of the forests. They can survive on the scanty water supply and so cover large areas at 4000 to 5000 feet. There are several species, *Juniperus Utahensea*, *J. monosperma*, *J. pachyphlœa*, and *J. scopulorum*, not very different in their several ring types and each rarely giving a specimen whose rings are readable enough for dating purposes.

West of the Arizona forested areas there lies the valley of the Big Colorado, a large, exceedingly dry area which might be called the climatic shadow of the higher mountain ranges of southern California whose westerly faces get a substantial rainfall. These ranges are the southern extension of the Sierra Nevadas that extend along the east side of California. Near the ocean there is a low coast range and between the coast range and the Sierra Nevadas there is the large, dry, interior San Joaquin Valley. The Sierra Nevadas form a high rampart effectually intercepting the rain-bearing winds that come in from the Pacific. In a number of favorable spots upon these mountains there are found the giant sequoias (*Sequoia gigantea*) at elevations of 5000 to 7000 feet. These magnificent trees have a remarkable capacity of withstanding the attacks of pests and fire and by strongly tapering shape maintain with extraordinary strength isolated positions on fairly exposed ridges. They gather together in large numbers in the intervening basins which are quite commonly swampy. In this environment they show more resemblance to the coast redwoods at far lower levels. In 1924 it was ascertained that the giant sequoias in the various groves from Springville on the south to Calaveras on the north have strong cross-dating characters. It was found that practically any ring sequence of a few hundred years may be dated in terms of the standard sequences developed in the King's River region. However, this cross-dating between trees is far more striking in the southerly groves, King's River area, Sequoia National Park, and Springville. The identification of the date of a ring is easily done in trees growing on the uplands and midlands, but becomes difficult in the basins where a continuous water supply permits the trees to have an increased rate of growth and great regularity from year to year.

While it is true that our chief studies have been done in the Colorado Plateau area, the enormous age of the big sequoias and their cross-dating qualities make them of the highest value. The exact dating of the rings of these giants was obtained by 1919. It is only recently that immensely long chronological sequences have been developed in the Colorado Plateau area, reaching back to A.D. 11. Although the early 80 years of this latter chronology come from a single tree, it is a Douglas fir and its record may be accepted as valuable, subject to future correction should other tree records be found.

The value of these two ancient coincident records covering 1900 years, at a distance apart of some 600 miles, becomes very great when we find that in cycle analysis they have a distinct resemblance. Meteorological records go back commonly less than a century and reach the hundred-year mark in only a few accidental spots, but in these trees we find ring records accurately dated reaching back to the beginning of our era, in two well-separated localities of which one maintains its sequence full 1300 years farther into antiquity.

Need and Function of Cycles—It is well recognized that development of long-range forecasting is highly desirable. This is true in any part of the country, but it is especially true in marginal lands that are subject to strong climatic variations from year to year—variations whose violence and time of coming are of the highest importance, because man's very existence in such places depends upon his power of adaptation to such changes. Changes of this sort become very graphic in the area under consideration. For example, Mormon Lake, the largest in Arizona, four by six miles in extent, was totally dry in 1901 when crossed by the writer. Now its shores have been a summer resort since 1909 and the lake is advertised for its fishing. What made it go dry, and how can we determine when it will go dry again? In the spring of 1935 the desert was covered with wildflowers, while in 1934 it was not. That is due to great difference in winter precipitation in the two years. What made that difference?

The problem of drought is more directly human than that. Hundreds of homesteads have been taken up in the semi-arid parts of the Southwest. The owners put in wells by which to pump water from a supposedly inexhaustible source below. But that source is not inexhaustible, since it comes from the rains which have fallen on a relatively small area. Too great enlargement of irrigated districts will make demands upon the water resources far beyond their replenishment. It becomes of vital importance, then, to know when the replenishment will take place.

Everyone who has lived long in this country has seen years of drouth and cattle lying dead beside dried-up water holes. People of early days learned how dangerous it was to travel long distances with horses without full knowledge of the technique of obtaining water.[1] They recognized that some years were far more severe than others in respect to drought; with no knowledge of what would come to pass, they must be prepared for the worst. Obviously our duty is to develop all possible methods of foretelling the future. Increase

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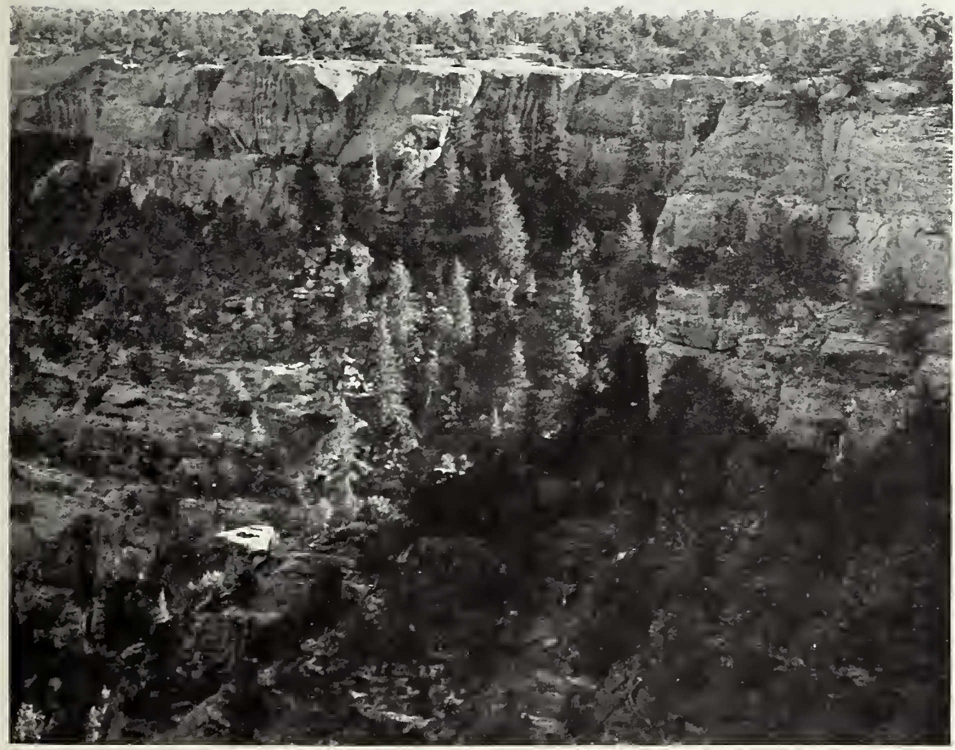
[1] In 1896 a young cowboy from Beaver Creek, Arizona, could not believe me when I told him that in New England we did not carry canteens wherever we went.



Douglas fir site, Mesa Verde: the tall trees (in center) showing in the sunlight are Douglas fir in typical site near their lower, dry, margin; view from Cliff Palace, Mesa Verde; the trees on the mesa top are mostly juniper.

Giant sequoia: "Lady Alice" in Balch's Park (1925).

of populated areas will make these problems more and more urgent as time goes on.

In a general way there are two approaches to long-range forecasting. One might be called the map method and the other the cycle method. The map method applies to short-range weather forecasting and delineates the position of storm areas, of polar fronts, and of air masses with definite characteristics. The average motion of these masses is well known and each day upon receipt of reports it is safe to make a short prediction by means of a series of maps indicating the temporary position and condition of the several factors. As these conditions become expressed for larger and larger geographical areas, the predictions can extend (less precisely) farther into the future. A meteorologist who understands the known factors and the mechanics of the motion of air masses can sometimes make predictions of value up to some months in advance.

Belonging to the same class, and yet depending on factors whose relationships are less well known, there is a form of prediction depending upon ocean temperatures. This basis of prediction is under special study at the Scripps Institution of Oceanography on the coast of southern California.

Long-range forecasting by a cycle method is highly desirable on many grounds. In the first place, the use of the forms of analysis described in this paper establishes the fact that an important proportion of climatic changes may be expressed in terms of well-defined periods[1] that have four to twenty-five or more repetitions. It is here believed that it is a mistake to neglect the examination of climatic changes because they do not seem permanent and exactly timed and are not molded in an artificial form like a sine curve. It is believed that many earlier investigators have committed an error because they disregarded variations that could not be expressed in terms of harmonic analysis. Observed variations have often been called accidental with the implication that they were worthless for investigation. Such an implication might be justified by the results of harmonic analysis, but should be reconsidered in view of the methods here used.

In the second place long-range forecasting by the cycle method is urged because in cyclogram expression there are evidences of relationship between climatic changes and solar variations. In the third place we naturally think of atmospheric phenomena on the earth as full of random changes, but these changes are found to agree over large areas of country and we conclude that we are encountering something general and highly important. Similarities over extensive geographical regions are among the important facts to be considered in this book (Chapter V).

But there is still another reason for investigating climatic cycles. We have developed accurately dated chronologies 1900 and 3200 years long which possess in some cases high climatic value. In these we are finding recurrent phenomena or repetition according to some plan. This new investigation we have reason to hope will compensate in substantial measure for the temporary character assigned to climatic cycles, and will contribute to the final climatic theory that opens the way to scientific long-range prediction.

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[1] The word "period" is used with a little stronger sense of precision and stability than cycle.

Period and Cycle—Some remarks should be given on the use of the words period and cycle. In general, the word period is extensively used in astronomy and refers to a repetition that comes at fairly exact intervals or whose variations from exactness are due to fully assignable causes. The best examples of periods are found in the motions of the planets. To cycle students the word has commonly meant continuous and unending operation at closely equal intervals. In these pages the terms discontinuous, or fragmentary or temporary are introduced before period to indicate fairly exact repetitions that seem to have a beginning or an end. The word cycle seems to us a more general term with fewer requirements as to duration and to the stability of its length, phase and amplitude. Thus we refer to the sunspot cycle as a series of discontinuous periods in order to describe the fact that it remains steadily at one period length through a number of repetitions and then changes slightly to some other value, to which it clings for a time. The sun's persistence in maintaining a slightly irregular fluctuation in the number of spots through the centuries is to some students a most suggestive connotation in the word cycle. The application of the methods described in this book gives the best apparent chance of demonstrating the existence of this character in climatic cycles.

Acknowledgments—Acknowledgment is made of the generous assistance given by the Carnegie Institution of Washington for our climatic studies since 1918. Aid from that source has been augmented in recent years, and at the present time a special grant is making possible our statement of results. This grant becomes effective by coöperative arrangement with the University of Arizona. The latter has given its assistance for many years in the way of laboratory rooms, and for a time, while extensions of the Arizona ring chronology were pending, made it possible for the writer to work without being subject to class schedules. Great obligation is due the National Geographic Society for its financial aid and moral support during several years when the Arizona chronology was being extended. To the Society, that extension brought about the successful determination of the age of the splendid ruin called Pueblo Bonito and other ruins of the Southwest; to us, it was, in addition, the extension of a climatic history into far past times in a favorable region. The publication of my report of the dating work is now made, and I appreciate particularly the gracious willingness of Dr. Grosvenor that the important collections made for that purpose may be freely used in climatic and other scientific studies.

Acknowledgments are also most cordially made to Dr. H. S. Colton and his colleagues of the Museum of Northern Arizona; to the American Museum of Natural History and other institutions through Dr. Clark Wissler and Mr. Earl H. Morris; to the Research Corporation of New York; and to many others, among whom the students of "tree-ring interpretation" should be

specially mentioned. In connection with this volume, my special thanks are due to Dr. W. S. Glock who made a careful review of the text, to Mr. Edmund Schulman who worked with the author on all cycle problems and whose tests of the analyzing instrument form the major part of the appendix, to Mr. Gordon C. Baldwin, Mr. A. N. Cowperthwait, Mrs. G. Dewey, Mrs. M. B. Koenig, Mrs. E. N. Strickler, and others whose valuable help has made it possible. The photographs of rings in this volume were made in our laboratories by members of the staff and especially by Mr. H. F. Davis. Landscapes were mostly taken by members of the staff. The drawings are largely due to Mr. A. J. Krutmeyer and Mr. Davis; cyclograms and special plates were made by Mr. Davis. I am very grateful to Dr. E. B. Wilson, Dr. John A. Fleming, Dr. C. G. Abbot, Mr. H. H. Clayton, Dr. S. B. Nicholson, Dr. D. Alter, Dr. E. F. Carpenter and others for their careful revision of portions of the text.

NATURE OF TREE-RING DATA

Trees—Our results have come chiefly from the cone-bearing trees of the Colorado Plateau, the ponderosa or western yellow pine, the Douglas fir, pinyon and juniper, already mentioned on a preceding page.

Ring Records—Trees are selected from areas in which obvious conservation of water, in brooks or swamps, does not occur; pests and fire effects are avoided. A line is marked from the center to the outside of a cross-section after the radius most free from defects and irregularities has been found; trees with obvious irregularities are not used. Measurements are made of the thickness of the ring, taken in the radial direction.

Measurements are made to 0.01 mm.; practically all measurements used in this book are considered good to about 0.03 mm., for the rings themselves vary slightly at different points. A few thousand made before 1914 had an average error of 0.06 mm. The series of rings, considered as to thickness, taken in any one radial or part of a radial from the interior out toward the bark is called the ring record of the tree. Obviously, the first fundamental fact deals with the uniformity of record in different parts of the tree. In taking borings in living trees, or in making V-cuts across the ends of logs, or in testing any part of prehistoric logs, or studying fragments of charcoal whose position in the tree is unknown, the value of such measurements clearly depends upon this uniformity throughout the tree.

Uniformity of record in pines and Douglas firs of the Pueblo area has been found to be fully satisfactory throughout my experience. I have searched thousands of times in the last twenty-five years upon full sections of northern Arizona trees of these species for identity of rings about the circuit, and never, except in the case of obvious injury, have seen any reason whatever to question a very satisfactory circuit uniformity in the pine and fir that we are using, nor, in fact, in the pinyon, although that is less universal.

Dissected Trees—In order to make direct tests of uniformity within the trees which we are using for chronological purposes, Dr. Glock and the writer selected pines in typical areas near Flagstaff, Arizona. Ring measures were made upon several radials about the circuit of the trees and at different heights; branches and roots were included; doubling and failure of ring formation were noted; the tip growth of the central axis of the tree was observed for the various years of the tree's life. The identification of the year of this tip growth is easy to anyone able to identify the adjacent rings. Detailed reports of this investigation will be given elsewhere;[1] it is enough to say here that the results exceed our expectation in every respect. The uniformity in the trees tested is beyond question. A single illustration of this sort of test is given in figure 1, which shows measures in six different radials distributed about the circuit of a Douglas fir, MLK-127, whose ring sequence is shown in the frontispiece.

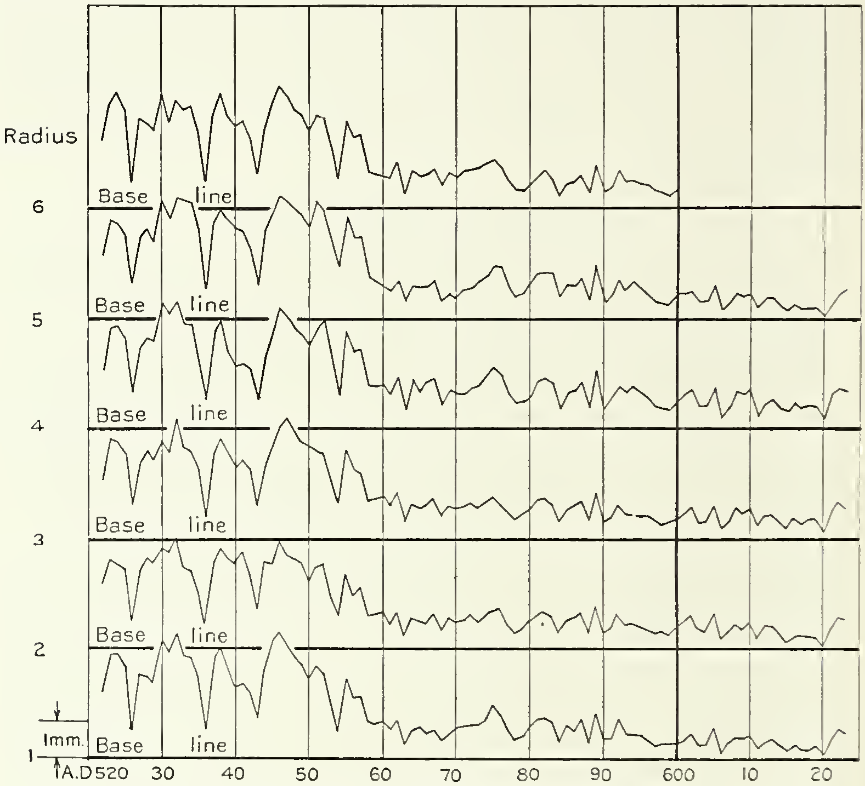

FIG. 1—Circuit uniformity in a prehistoric Douglas fir MLK-127 from Northeastern Arizona. See frontispiece and figure 11.

Types of Ring Records.—While such uniformity within a tree is fundamental, we encounter certain differences in type of record in different trees of a forest. Some records have the rings all essentially of the same size, or presenting slow changes from one size to another depending upon the age

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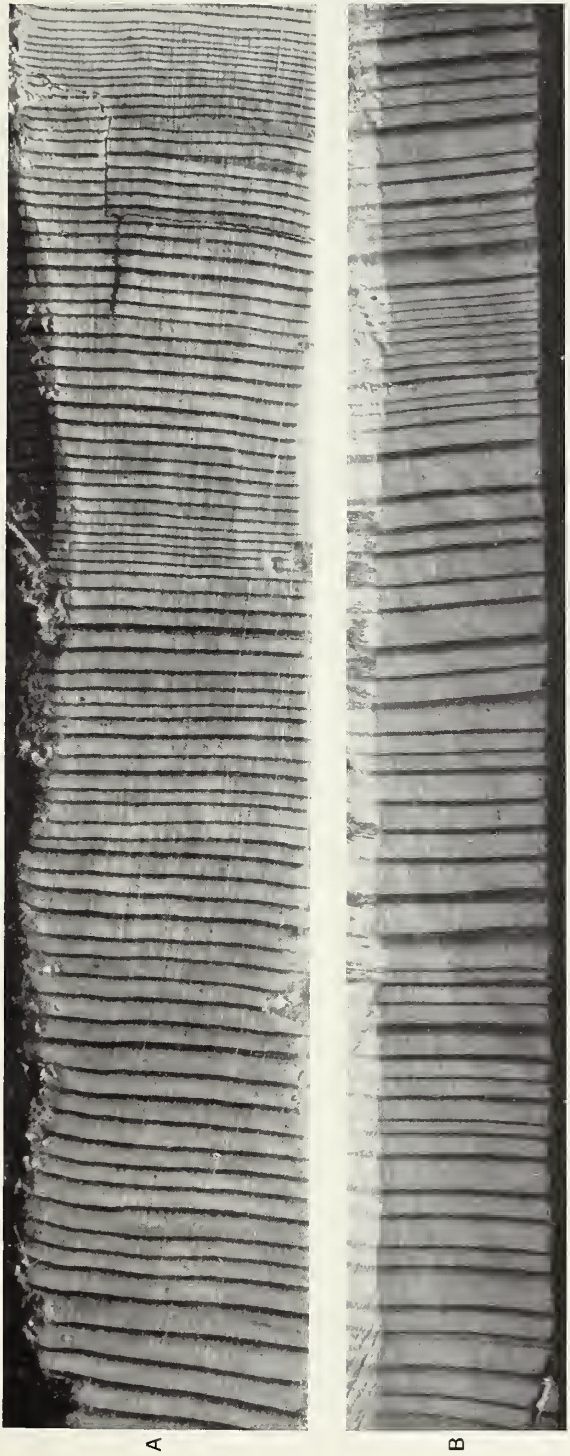
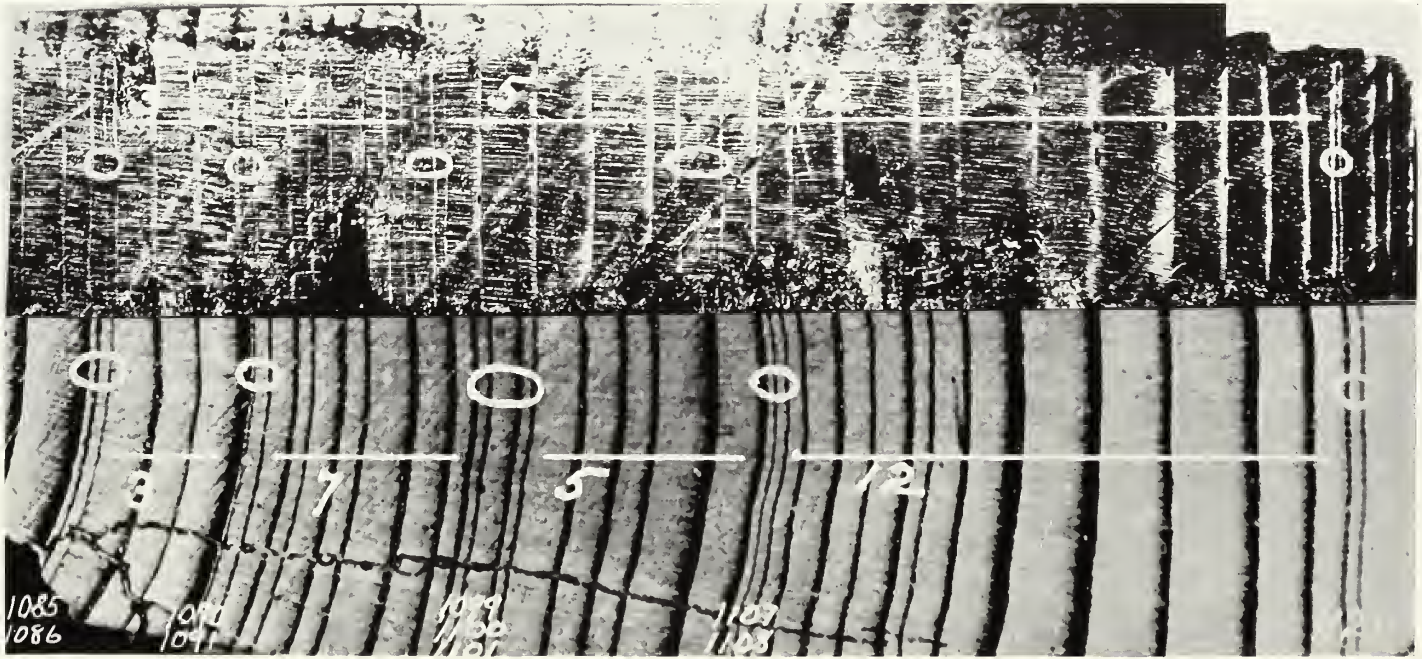
[1] These reports are now in preparation by Dr. Glock, to appear as a separate paper.



Complacent and sensitive sequences of rings:
A. Complacent ring record, BE-133, pine.
B. Sensitive ring record, MV-23, Douglas fir.



Cross-dating at 125 miles, JPB-17, pine, above, and BK-2, Douglas fir, below, by identification of corresponding ring patterns; identification is usually done as in this case by finding equal intervals between the small rings.

of the tree, as we estimate them one after the other from center to outside of the tree. This kind of series is called "complacent." Other ring records contain strong increments from year to year, such as evident in the curves shown in figure 1. These are called "sensitive" records. Examples of these two types are given in Plate 6 which shows a very complacent ring series in BE 133 and a sensitive series in MV 23. Apparent correlation could be very high between complacent records and yet such records usually contain no identification characters and often are valueless. Hence, another character is needed; this has been expressed in previous years as "mean sensitivity." Mean sensitivity is the average percentage increment from year to year without regard to sign. A tree of high sensitivity is more datable and more likely to make a contribution to our studies than a tree with a complacent series of rings. This sensitivity, of course, is only determined where there is no perceptible injury.

Cross-Identity—Cross-identity which is established by a process called "cross-dating or cross-identification," depends on the sensitive type of ring sequence. It is the foundation stone on which long ring records have been based. In modern trees it involves the determination of the exact year in which each ring grew.[1] There are three practical steps in this process. First, one counts in from the bark of trees whose outermost ring has an obvious date—for example, the outermost ring in a tree just cut down—and thus finds the exact dates for various thin or otherwise well-characterized rings. Second, a careful note is made of the time spacing of the specialized rings, which may now be regarded as a recognizable group, and search is made for an identical group in another tree of unknown cutting date; when found the group rings in the latter tree become known as to exact date. Third, in the second tree, a count is now made either to the outside to find when it was cut, or toward the center to ascertain the exact dates of earlier groups of specialized rings. All this is easily practised in a logging camp where many stumps are available. On such stumps near Flagstaff anyone can always count from the outside to some distinctly small ring or group of rings and find exactly the same count from tree to tree except in the rare cases where some severe drouth year has occurred that caused the failure of ring formation in a few trees. The identification may then be carried to stumps cut years previous to the dating and the date of their cutting ascertained for checking against forest records. In this way confidence in the method is easily acquired by anyone who will take the trouble to test it in a favorable locality, such as the Flagstaff region.

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[1] The word correlation has been suggested in place of the words here used, identification and dating. Such a change would abandon the most important fundamental of tree-ring work, which is the establishment of identity of the growth-date of the individual ring. It is not resemblance or relation or correlation in date that we endeavor to fix, but the actual identity of date, and all the other points of interest and value flow from that. The significance of cross-identification and correlation is clearer in the statement that the *cross-identification* of a ring depends on *correlations* between ring distribution within groups and other characters in two or more different sets of rings.

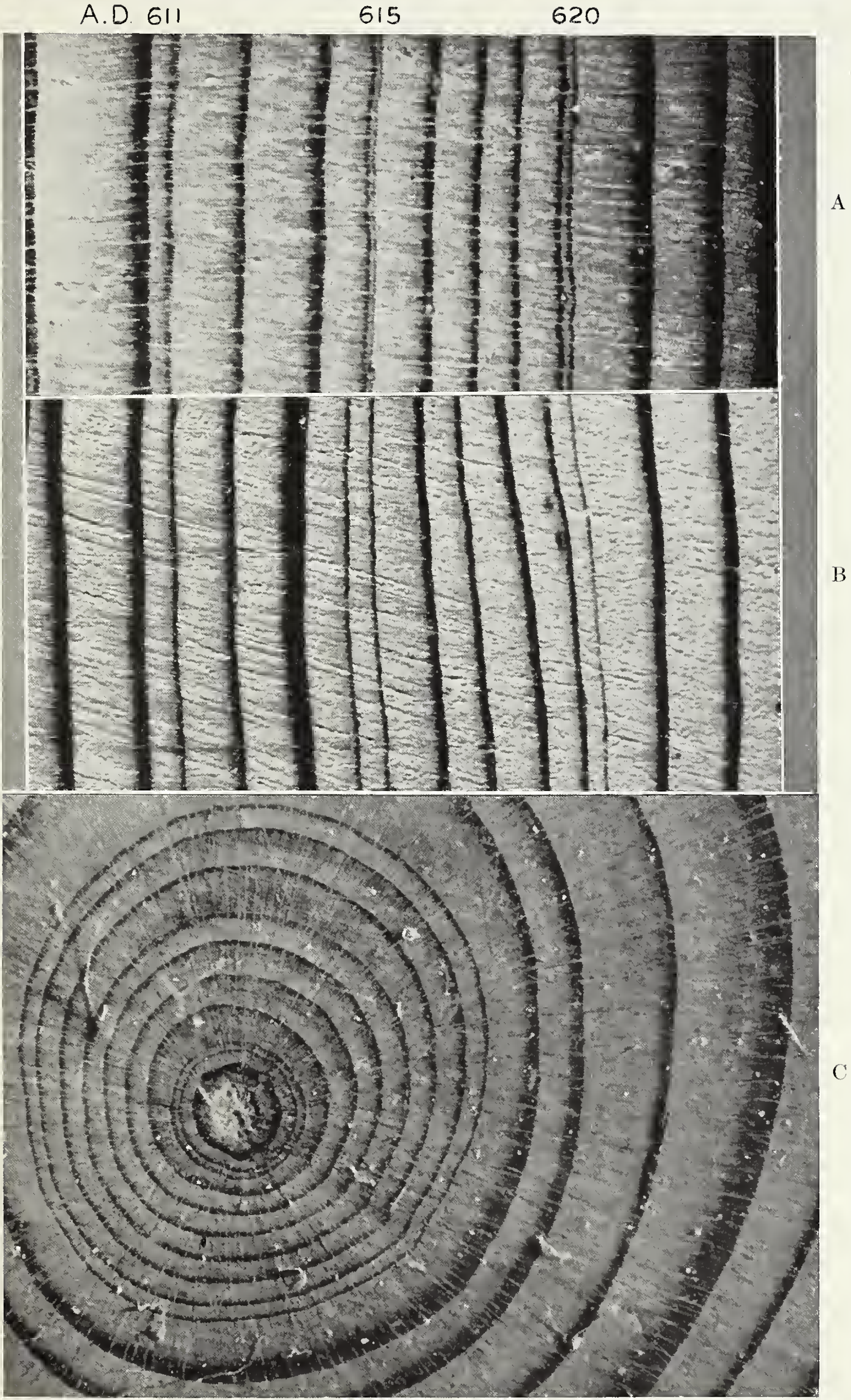
A definite ring sequence is usually first proved by showing the common identity in date of rings within a number of trees without thought of the actual dates; hence the word *cross*-identity or cross-dating to convey the idea that the identity must be carried across from tree to tree (and not taken merely within a tree). If this cross-identity can be established, then the student is well on the road to actual dating.

Cross-identity was observed in 1904 and recognized as a fundamental part of tree-ring work in 1911. From the start it was realized that chronological identification can be carried from tree to tree by grouping of the rings themselves as described above. Cross-identification, therefore, depends on a succession of specialized rings which, as a group, do not occur in other parts of the long chronological ring record. Thin rings are found more useful in Arizona in this identification process than wide rings, because ring records from different trees show better correlations in thin rings than in wide ones.

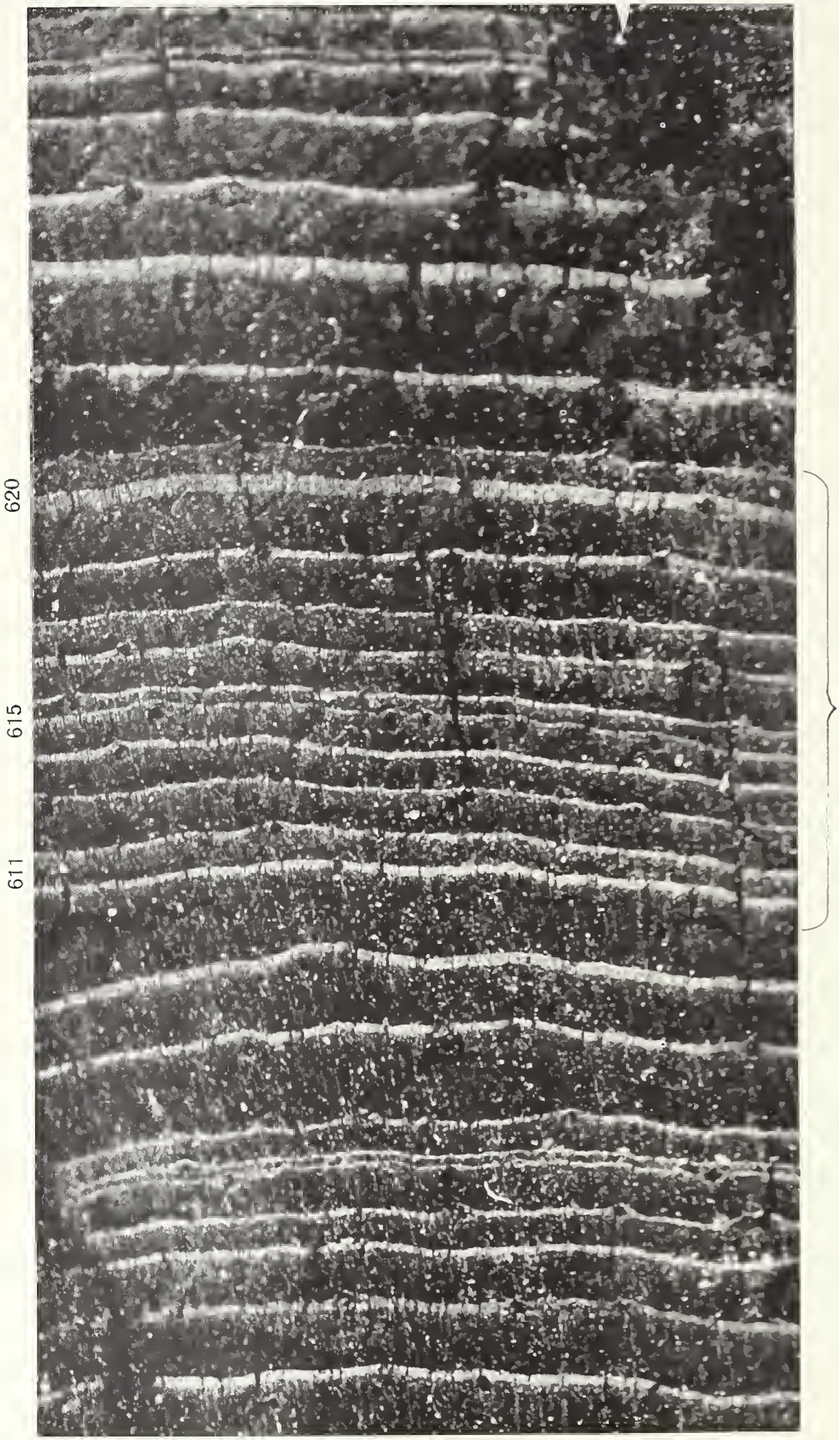
Thus a short series of 10 or 20 rings is not usually datable—that is, it can not convincingly establish a cross-identity, but if seemingly recognized it may serve as a guide and when these rings are joined with twenty on each side also recognized the series of fifty usually becomes datable. Thus, commonly, fifty years is considered desirable for cross-dating. Occasionally sequences with some conspicuous grouping of the rings may be considered datable if containing twenty or twenty-five years. Often a sequence of a hundred can not be dated because it does not contain enough deficient rings to render identification possible by comparison with other trees.

A highly typical case of cross-dating is shown in Plate 7, which represents, above, a series of pine rings near the outside of JPB-17 from Pueblo Bonito, and, below, a Douglas fir BK-2 from Betatakin, 125 miles away, giving rings near the center of the tree. In spite of these differences and the great distance apart, the spacing of the deficient rings as indicated is identical in the two trees.

Compact groups of rings which appear almost identical in many different trees are sometimes called signatures or fingerprints. Plate 8 gives a series of rings showing a compact group from A.D. 611 to 620 which was recognized as a specialized group many years before its date was ascertained. It appeared in M-179, a beautiful Douglas fir specimen collected by Mr. E. H. Morris in 1927. Then it was recognized in 1931 as a part of the JCD (Johnson Canyon Dating) series from the upper La Plata River near Mesa Verde National Park, and it has come to be called the JCD signature. It was recognized in 1932 in very beautiful form by Dr. Glock in the MLK series from Broken Flute Cave west of Shiprock. In the latter part of 1934 it was found in a charcoal section, FR-20, collected at Allantown, Arizona, by Mr. C. F. Miller under the direction of Dr. F. H. H. Roberts Jr., for the Smithsonian Institution. In early 1935 it was found on a charcoal piece, F-3992 (Plate 9), from the Baker Ranch Ruin north of the San Francisco Peaks, Flagstaff, collected under the direction of Dr. H. S. Colton for the Museum of Northern Arizona and handed to me by Mr. J. C. McGregor, who does the tree-ring work for that Museum. These locations form a triangle whose three sides are approximately 95 miles, 150 miles, and 160 miles. Plate 8c shows the center of MLK-179, whose central microscopic ring grew in the year A.D. 536 and corresponds to the 15th ring from the center of MLK-127, shown in the frontispiece.



Enlargements of specimens shown in frontispiece.
A. MLK-179, showing JCD signature, A.D. 611 to 620.
B. MLK-127, showing same.
C. Center of MLK-179: the microscopic ring at center is A.D. 536; it is the small ring, fifteenth ring from the center, in MLK-127.



JCD Signature in F-3992, Flagstaff (charcoal). Courtesy of the Museum of Northern Arizona at Flagstaff.

In connection with cross-dating, figure 2 has been arranged to show similarity in measured values over a small area by comparing the growth records of five pine trees collected within an acre near Prescott, Arizona, in 1911. The mean mutual correlation coefficient of each to the other four is 0.85 ± 0.02. Better agreement is noticed in the rings of deficient years than in the wider rings. Figure 3a shows the agreement between curves obtained from two groups 70 miles apart; one consists of seven pine trees near Fort Defiance (LCFD); the other has three Douglas firs (group name PNN) from a location called Pinyon in the south central part of Black Mesa.

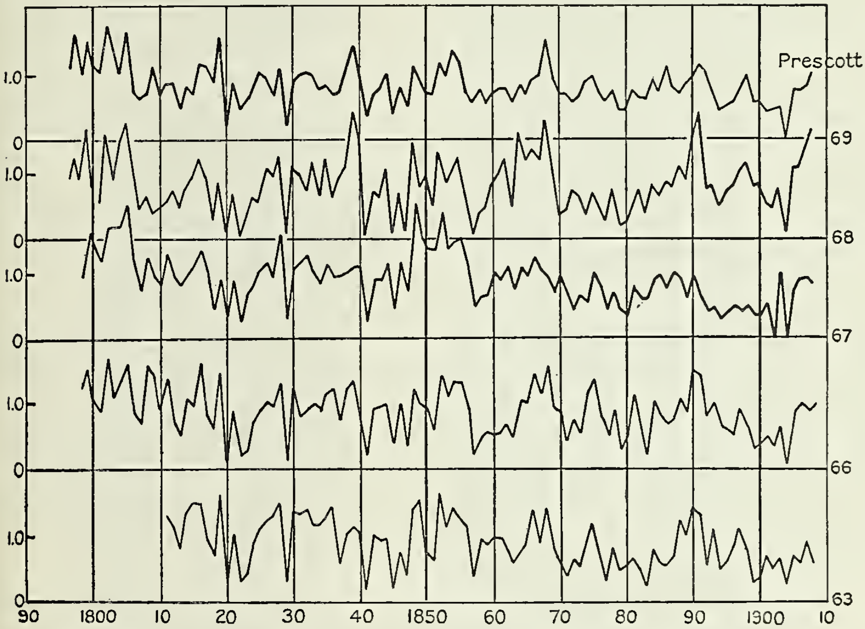


FIG. 2—Cross-identity (similarity of growth in each year) in Prescott trees.

The examples of cross-dating over this area are so tremendously numerous and the similarities so striking that these ring resemblances over the Pueblo Area assume the proportions of a phenomenon which has been overlooked because of the stronger human interest in the dating of prehistoric ruins that became possible through its agency. Up to the present time only a few miscellaneous examples of cross-identification have been published out of many thousands. It is hoped that a large display of it will be made in a forthcoming volume.

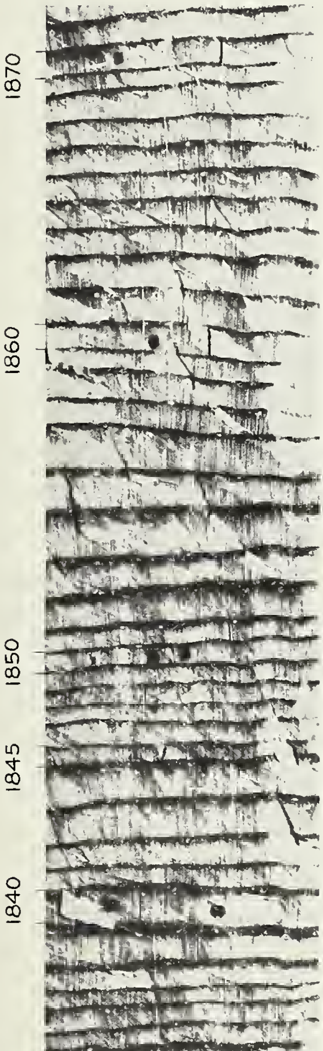
RING TYPES AND TOPOGRAPHY

The importance of cross-identification described above was first thoroughly realized in 1911 after comparing ring records in trees near Prescott, Arizona. An excellent group from near town, whose location I visited at the time, gave a highly sensitive sequence of rings with immense and sudden changes from one ring to the next. (See Plate 10B.) A certain questionable ring in these trees—namely, 1904—was settled by cross-identification with Flagstaff 70 miles away. The twenty-five Flagstaff tree sections used at that time gave less pronounced correlations among themselves, for their ring records were relatively complacent. This was later recognized as a different ring type, namely, the "forest interior" type showing rings of low sensitivity, though not really complacent; the thin rings used for identification were there, but were not often highly conspicuous because of their smallness. In 1919 a collection was made at Aztec, New Mexico. In 1922 a large collection of ancient specimens was begun from the Indian country located on the Colorado Plateau between Flagstaff and the Rio Grande Valley. It is very obvious to one who knows this region that the Indians selected residence locations at the lower forest border and from there on down into the desert and cut their building timbers from the trees of the neighboring forest edge. Many of their ruined villages, now miles from the forest, contain thousands of pine logs. Many ring specimens have been secured from these logs, and in 1927 serious work on them began. By 1929, with the aid of field trips financed by the National Geographic Society, dated sequences were carried back to A.D. 700.

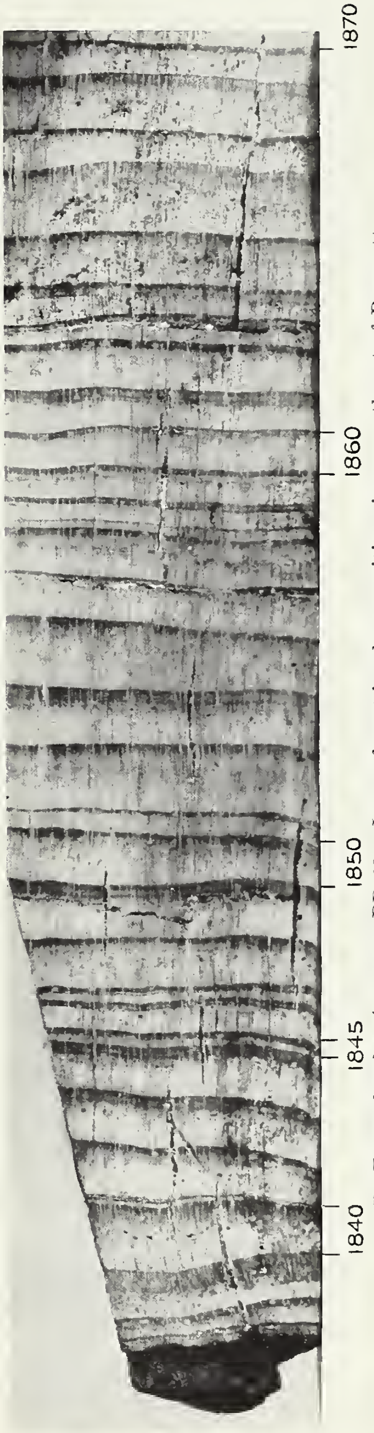
The character of the prehistoric ring sequences used in constructing this early chronology was at once noted as different from the general character previously observed at Flagstaff in modern tree growth (Plate 10A). There were sudden and pronounced differences in ring thickness from year to year. This made cross-dating almost infallible if conducted with care in the selection of uninjured and sensitive specimens. It was at first thought that this difference was a climatic change during the centuries. But that idea was quickly destroyed by finding highly sensitive modern trees in the Pueblo area and complacent records from ancient trees near Flagstaff.

In connection with the early attempts to date this prehistoric material, this difference in ring type was investigated more carefully. Between 1922 and 1927 many individual collections were made around the Pueblo area for the purpose of establishing in modern trees the existence or non-existence of cross-dating over that area. Obviously it would be of little use to spend large sums of money in excavating prehistoric ruins only to find that the process failed and left us without results for the money expended. We were able to see as a result of these collections that such dating was highly reliable between Flagstaff, the Hopi Villages, Black Mesa, Kayenta, Mesa Verde, Chaco Canyon, Chin Lee, Fort Defiance, and the "Rim" eighty miles south of Flagstaff. Ease of its application was found to increase as one left the forest center and worked nearer the desert. At the very desert edge the trees may become difficult from absence of rings. This area outlined forms a rough circle about the Chuska-Lukachukai mountain range, and has therefore come to be called the "Central Pueblo Area."

Effect of Local Topography—There still remained characters in the ring sequences found that were not explained thus simply by geographical location



A. Forest interior ring type—Pine, FL-131, 3 miles north of Flagstaff.



B. Forest border ring type, PR-62. Lower forest border, sensitive rings; southeast of Prescott.

Tree roots and bed rock, Defiance Plateau. These trees give good climatic records.

with reference to the forest border. It had been quickly recognized in the big sequoias between 1915 and 1918 that there was a great difference in mean ring thickness and in sensitivity of ring series, depending on the location of the individual trees with reference to character of water supply. High sensitivity was found in trees growing on the steep slopes of the uplands. Large rings, low sensitivity and complacent sequences were found in the swampy basins. The mean growth in the basins sometimes was four times as great as that on the uplands and ridges. So relation to water supply was studied in the pines about Flagstaff and it was realized that trees near a constant water source had larger rings and less sensitive sequences than those growing where there was little or no chance for accumulation and conservation of water. A special search for particularly favorable locations in the Arizona regions was made by Dr. Glock and the writer in 1934, with the result of finding sites where the sensitivity was so high as to introduce many difficulties from absent rings. Interesting series of this sort were obtained from Defiance Plateau between St. Michaels and Ganado at elevations near the lower forest border. The soil is exceedingly thin and here and there sandstone shows above the ground. Plate 11 shows the stump of a tree that had been blown down at this site, whose roots penetrate the cracks between large blocks of sandstone. In these trees the sensitivity of the record was exceedingly high.

One other term in the environment of Arizona trees was observed at a sufficiently early date to appear in Volume I of *Climatic Cycles and Tree Growth* (page 22), namely, the nature of the soil; and our present knowledge is only the beginning of a complex subject. Near Flagstaff there are roughly two chief soil types: one has formed on limestone with a varying admixture of sandstone products, and the other rests on volcanic rock. The former rocks decompose into a porous soil from which moisture readily escapes and the rocks themselves possess deep cracks, as may be seen in many places about Flagstaff. The volcanic rock decomposes into a clay soil which holds water very tightly but usually in small quantity. When the two soils are adjacent and somewhat similar in contours as at points near Fort Tuthill, five miles south of Flagstaff, the ring records on the lava soils are relatively complacent. In the deeper soils and higher precipitation of the forest interior the growth seems larger but still complacent. In locations where the soil is topped by a granular mulch that aids conservation, the growth in dry years may remain small while that in wet years may increase greatly. This results in a sensitive record, as in OL-12, the dissected tree referred to above, which grew in the "cinder" area northeast of Flagstaff. (Measures of ring growth in this area made at the Museum of Northern Arizona by Mr. John C. McGregor show large growth.) Thick rings in wet years occur also in the granitic areas near Prescott, Arizona, as shown in specimen PR-62 in Plate 10B.

Significance of Cross-Identity and Cycles in Tree-Ring Records—It is evident at once that cross-identity depends on similarity in the records of different trees; it may extend over considerable areas; it is obviously not accidental, but comes from climatic factors in the environment common to the trees of the area. The study of cycles given below seeks to extend this investigation of similarities in the environment by picking out the slower and more prolonged reactions in tree growth to climate by the aid of a new method of analysis. At the same time, the expression of ring records and other forms of long records in terms of cycles puts their details in a form more compact and more readily available for human use.

RAINFALL CORRELATIONS IN NORTHERN ARIZONA

The powerful cross-identity over the plateau area of northern Arizona and northwestern New Mexico has raised the question: What are the climatic or other elements that make it possible?[1] Extended discussion of that important problem will be reserved for a future volume. It is proposed here to give only a very few of the facts. Before 1919 it was found that in the time from 1867 to 1910 rainfall and ring growth at Prescott, Arizona, had a correlation coefficient of about 0.52 ± 0.05. This rose to well over 70 per cent when a conservation correction was introduced. Rainfall and tree growth near Flagstaff gave an unsatisfactory correlation which was somewhat improved by using winter rainfall only. The trees used in this comparison were from the forest interior and so were less sensitive than those used in the Prescott tests.[2]

In 1933 Dr. Glock and I attacked the problem of ring growth and rainfall once more, using a number of our most important growth curves representing some sixty trees from various parts of the area centering on the Chuska Mountains. Rainfall curves were constructed from the longer records at Flagstaff, Prescott, and Natural Bridge. It was found that the direct correlation was again between 50 and 55 per cent. The introduction of a conservation factor based on a lag in smoothed curves observed by Dr. Glock, raised the correlation coefficient to between 70 and 75 per cent. When, however, the rainfall curve with conservation and tree-growth curves were smoothed in the fashion used for many years in cycle analysis (using a running mean of three with double weight at center), the mean correlation coefficient between rainfall and tree growth rose to 80 per cent. In figure 3b, the curves showing this relationship are reproduced. Figure 4 extends the comparisons by giving the runoff of the Rio Grande and the Colorado River near the northern boundaries of New Mexico and Arizona, and corresponding curves of ring growth. Figure 5 shows similar relation, less close, between southern California rainfall and tree growth in the San Bernardino Mountains and in the giant sequoias.

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[1] Carnegie Inst. Wash. Year Book No. 32, 1932–33, p. 209.

[2] Mr. W. E. Davis, at Berkeley, made in 1933 a series of measures upon increment cores secured by Mr. Pearson at the Fort Valley Forest Experiment Station, Flagstaff. His results were not at all promising for a relation between ring growth and winter precipitation. On examining the specimens used by him, I found them all giving complacent records, and that the better ring records had been discarded on the ground that the ring identity was uncertain.

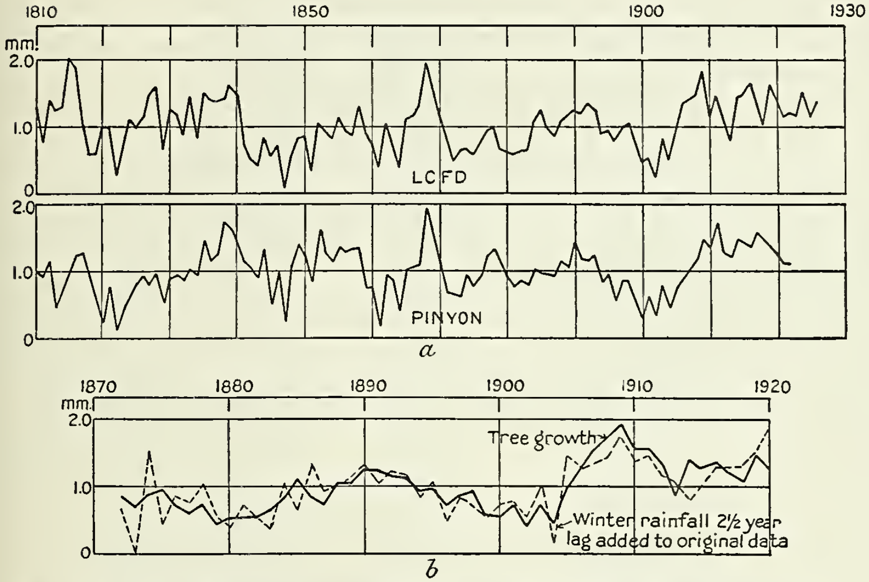


FIG. 3—a. Cross-identity at 70 miles, Fort Defiance and Black Mesa groups.
b. Winter rainfall with 2½ yr. lag in smoothed values, and tree growth.

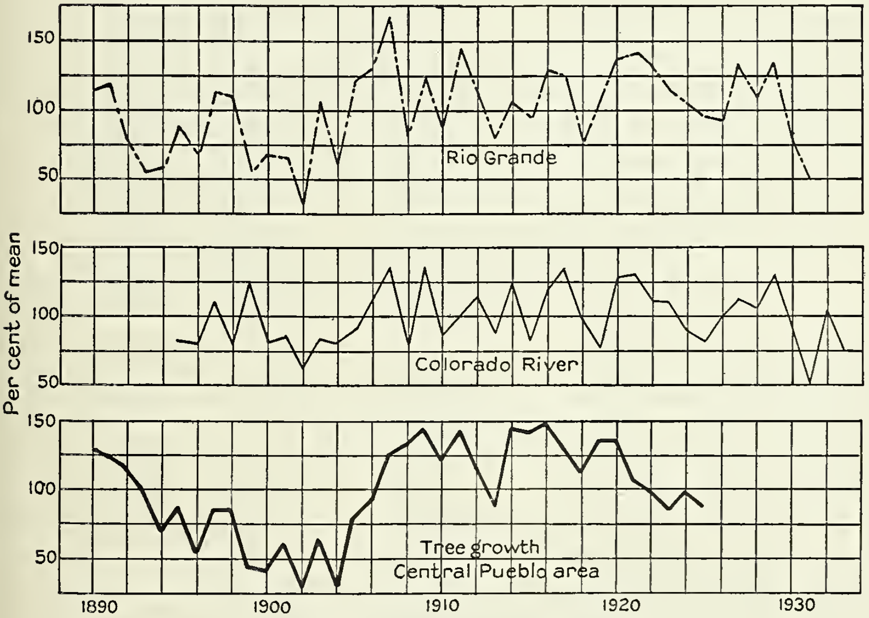


FIG. 4—Tree growth and river run-off.

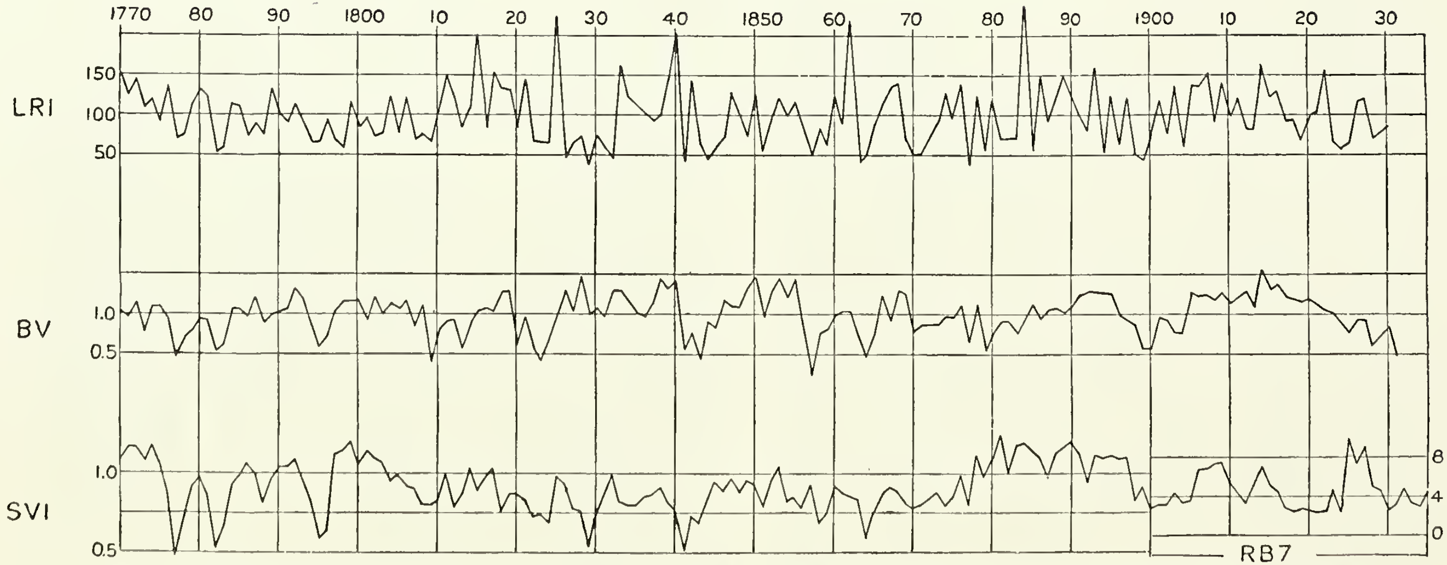


FIG. 5—Lynch's rainfall indices 1770 to 1930 (LRI) compared to Bear Valley pine record (BV) and Grant Park sequoia record (SVI) with a pine, RB-7, showing good sequoia record supplying data for the period 1900–1934.

II. CYCLOGRAM ANALYSIS

GRAPHIC EXPRESSION OF DATA

Definitions—During this study of cycles and the development of a new method of their determination, the meaning of certain special words has suffered some modification. So in the somewhat unfamiliar paths of cycle study, it is well to clear the way by a brief review of several semi-standardized expressions for use in subsequent description, and not as an exhaustive study of technical words.

An "extended" curve is one that represents an unbroken series of data through a succession of equal intervals of time. Such curves may take the following forms:

A. Unmodified or Primary Curves

1. "Original" data, unmodified by special treatment.
    a. Columnar plot.
    b. Point plot.

B. Modified or Secondary Curves

2. "Smoothed" curves.
    a. Running means.
    b. Hanned curve, or weighted running mean, sometimes called second or fourth intermediates.
3. Mass diagrams and residual mass diagrams.
4. Logarithmic plots.
5. Skeleton and increment plots (simplified curves).
6. Standardized and equalized curves.
7. Merged curves.
8. Compressed curves (a technique for handling long series of data).
9. Curve character figure; mean sensitivity.
10. Curve comparisons; correlation coefficient.
11. Curve summaries; the periodogram.

Original Data—Original or primary data are data that are unaltered; these words distinguish them from integrated or summated data (see below) or mass or smoothed or otherwise secondary expressions of data. The original plot, which gives a series of values at definite time intervals, may be columnar or point, illustrated in figure 6. The latter is the common form but neither is perfect. The columnar plot emphasizes only one value during the time interval between plotted points. This interval is one year in most of our curves. In tree-growth plots, this is accurate, for only one value is commonly measured for the year. But in rainfall it is less satisfactory as the known monthly variations are lost sight of. The common plot with lines drawn from point to point clips off the corners of the columns and suggests an even change from the center of one year to the center of the next. This has been regarded by the writer as a form of smoothing. It is the beginning of that general process, the grouping of details together in order to bring out the larger characters.

Smoothed Curves—There are two methods of smoothing in current use, the unweighted and the weighted running mean. An unweighted or common running mean of three is an average of each three successive terms placed as a substitute for the middle term. The common weighted running mean used for many years gives double weight to the central term. The formula for it is:

$$Y'_n = \frac{Y_{n-1} + 2Y_n + Y_{n+1}}{4}.$$

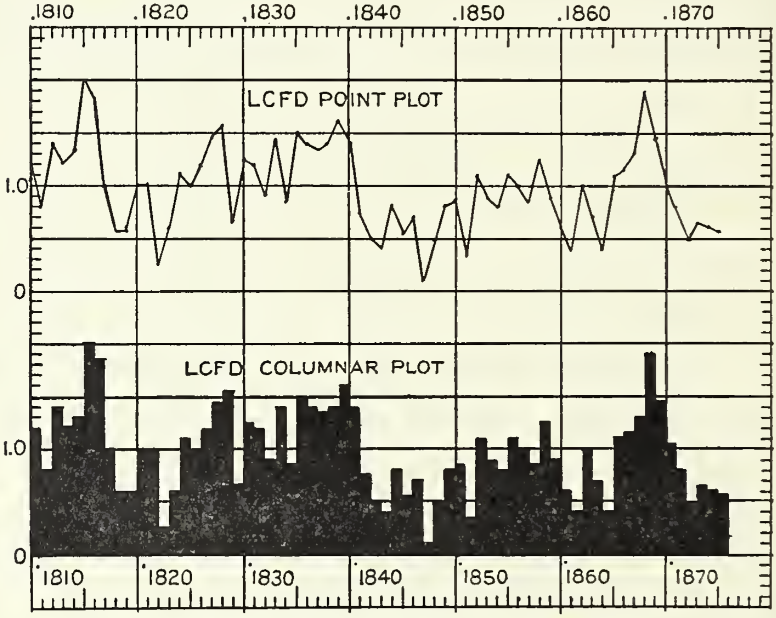


FIG. 6—Point and column plots of same data.

In our usage this method is adopted to the complete exclusion of simple running means because the latter in case of rapid alternations may bring a maximum where a minimum should be and *vice versa* (fig. 7. See also fig. 30).

This weighted running mean has long been called the "Hann" (the word has also been used as a verb) because applied extensively by Julius Hann. It is conveniently worked by actual figures as a "second intermediate." In this process the average of each two successive values is placed between them, but in a separate column, and then the process is repeated for the new column thus formed. The quantities thus obtained give the exact values of this weighted running mean and are often called Hanned values or second intermediates. In rare cases two more intermediates have been taken; the formula then becomes

$$Y''_n = \frac{Y_{n-2} + 4Y_{n-1} + 6Y_n + 4Y_{n+1} + Y_{n+2}}{16}$$

The Hann is especially useful in a very rapid graphic application, giving a result very close to the exact numerical value. Any difficult case may be solved quickly by slight additional care. If in an ordinary plot each three points in succession be taken as a triangle, and the distance from the middle of the base (connecting terms 1 and 3) to the central term be considered, then the point $\frac{1}{3}$ from base to the central term is the running mean of 3 and the point $\frac{1}{2}$ from base to the central term is the Hanned value or second intermediate, giving double weight to the middle term. After trifling practise, this is quickly done by hand on a plot and any doubtful case may very easily be measured. Figure 7 shows the original data (solid line) and the same smoothed by second intermediates (broken line) which is practically the same as the "graphic Hann," and also smoothed by a running mean of three (dotted line). The figure shows that the weighted mean introduces less distortion into the original data. Very long running means have been abandoned in favor of a general treatment of long curves that will be described below.

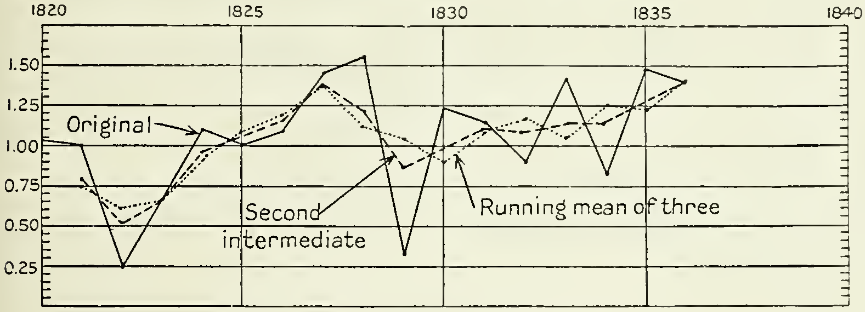


FIG. 7—Smoothing methods compared.

Mass diagrams and residual mass diagrams are secondary curves much used by hydraulic engineers because they show totals and trends (fig. 8). A mass diagram sums up in a single ordinate the totals contained in the preceding data. For example, it may be the continued sum of the intake of a reservoir and shows easily the total amount entering since any given date. The curve inclines rapidly upward. For water use it is convenient, but for climatic studies in which causes are sought, it is not well adapted, since the latter requires the knowledge of the ratio of any one year to any other year and that is not easily obtained from a mass diagram. The residual mass diagram is the same thing as the mass diagram, except that departures from the mean are used each year in place of the full values. The curve therefore assumes an average horizontal direction and is the continued algebraic sum of departures from the mean. This same thing has been called "accumulated moisture" by the meteorologists. A defect in this sort of curve is that it has a quite arbitrary point of beginning that modifies subsequent values. Since it adds together successive departures in the same direction, it sums up favorable or unfavorable conditions into extreme departures that greatly exaggerate the trends; hence small variations in the original data tend to disappear.

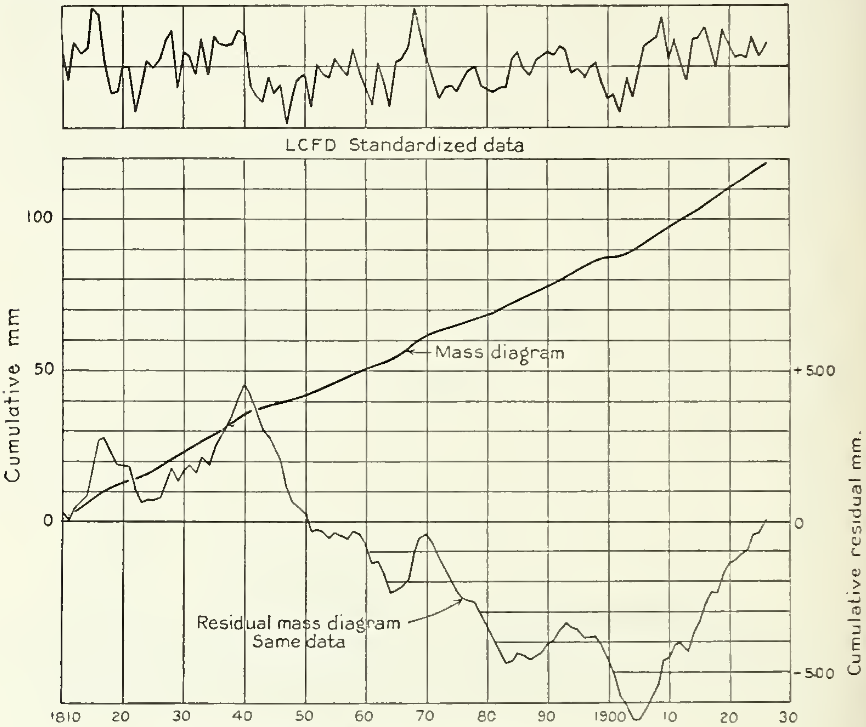
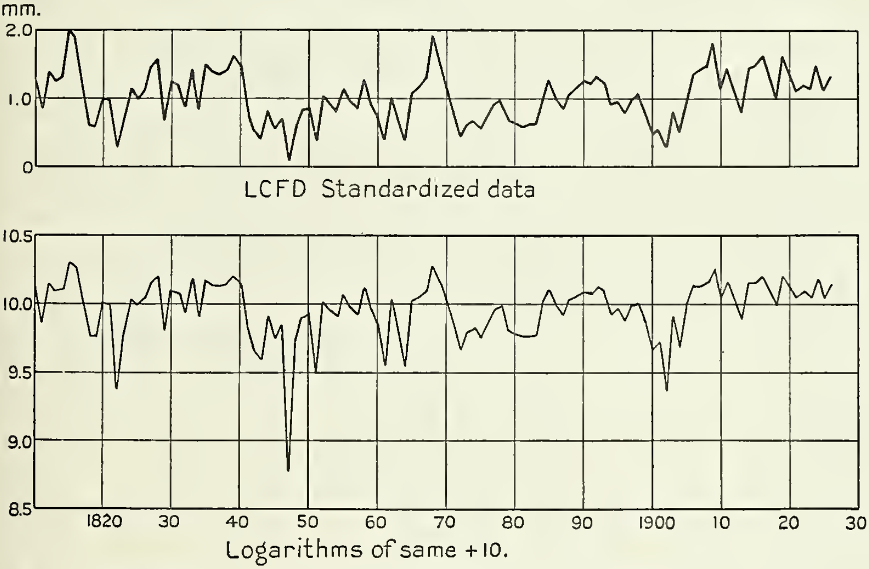


FIG. 8—Mass diagram and residual mass diagram.

When applied to a cycle, it makes the maxima and minima far more conspicuous and moves each forward a distance which for the sine curve is one-quarter of the cycle length. In that capacity it was used in 1919 to express a conservation effect in the relation of rainfall at Prescott, Arizona, to the ring growth of trees nearby. In all usage of these mass diagrams for cycle purposes it should be remembered that these are modified expressions of the original data and hence what they show is more complex than the original data, and special care is needed to see that something fictitious is not introduced. I have personally hesitated to use them because they are not a primary expression of data, but it is not easy to say why cycles derived from this sort of curve are not to be given careful consideration.

Logarithmic plots (fig. 9) have been little used in our studies so far as the original data are concerned. In logarithmic curves, the logarithm of each term is substituted for the term itself or the data are plotted on paper whose ordinates are divided into logarithmic spacing. The general effect is to lessen the relative importance of high values and increase that of low values.

Although not found convenient for use up to the present time, the logarithmic proposal introduces a general problem whose solution is not herein forthcoming. In expressing the thickness of rings, an absent ring receives the value 0, but such a value in a curve is by ratio indefinitely farther away from the mean (considered as unity) than, for example, 2.00 is, but as drawn in the common curve of rain or tree growth it is an equal distance. Are data such as annual values of rainfall and tree growth best handled in terms of addition and subtraction or by ratios? Should they be regarded as quantities above a base or departures from a mean? When correlation coefficients are taken, the data are merely regarded as departures from a mean and the position of a real basic zero line need not be known. But rainfall and tree-ring values do not cling around a mean in any such manner as micrometer measures of a planet's diameter, for example.



LCFD Standardized data

Logarithms of same +10.

Fig. 9—Logarithmic plot (below) compared with non-logarithmic plot (above).

It is to judge this latter type of observation that normal distribution and probable error were invented. We can evaluate some curves by determining the "distribution" of their values; that is, the frequency of occurrence of each separate value whether considered as a departure from the mean or as an amount above a base. In normal distribution (see fig. 10a) there are many values close to the mean. This is the case in measuring a definite quantity like a planet's diameter. Rainfall data usually give a "skew" distribution, non-symmetrical on the + and − sides (above and below the mean). Complacent ring records show a symmetrical distribution with far too many values near the mean (see fig. 10b); sensitive records show a skew distribution with increased numbers away from the mean (see fig. 10c).

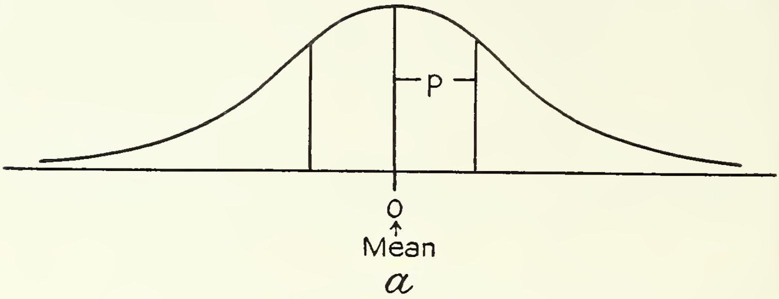


Fig. 10—a. "Normal" distribution of data about mean.

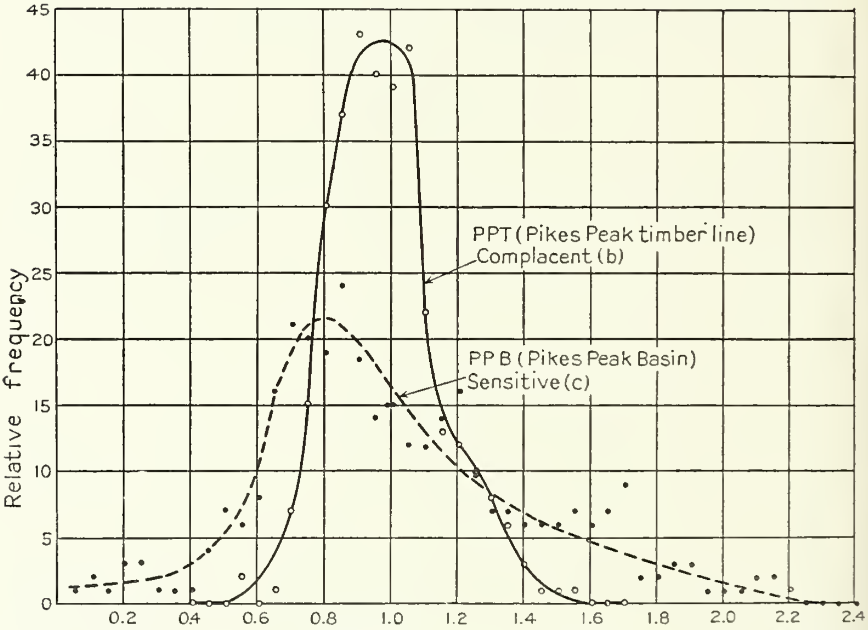


Fig. 10—b, c. Frequency distributions compared: standardized rings widths in complacent and sensitive records, 1750–1920.

At various times attempts have been made to plot curves in different ways referred to above to see if any advantage became obvious. But none appeared and it has always been felt that the simplest possible presentation of the data was the most advisable.

The *skeleton plot* (fig. 11) was used as early as 1921, but came into extensive use in 1927 for the cross-dating of rings. It simply represents in proper time order the notably undersized rings in any series. In Arizona similarities carry over from one tree, to another better in such rings than in the thick ones. Wet years probably lead to more conservation of water and food than dry years. This aids the tree, but the amount of aid is greatly influenced by topography about the tree, and so trees show some differences in growth.

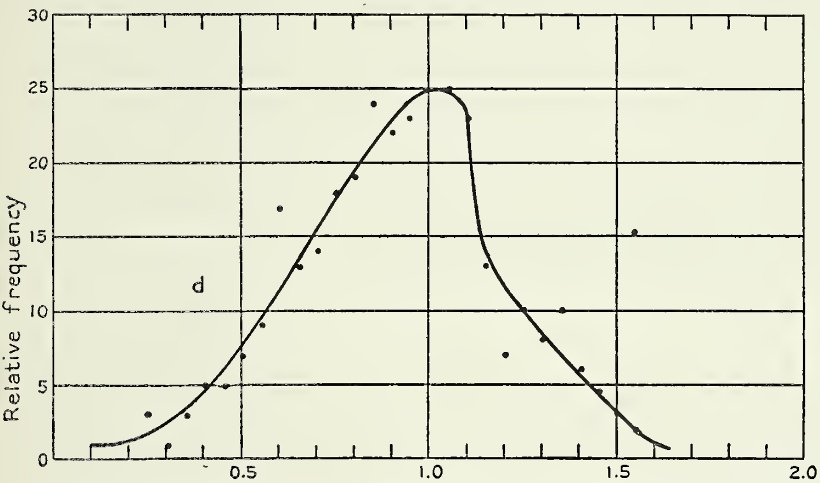


FIG. 10—d. Frequency distribution: standardized ring widths in sensitive records, Central Pueblo area. Mean group curve (73 trees).

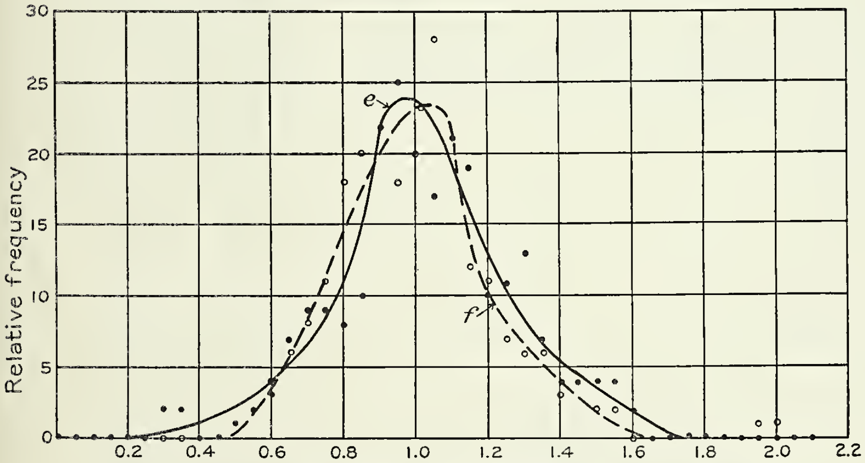
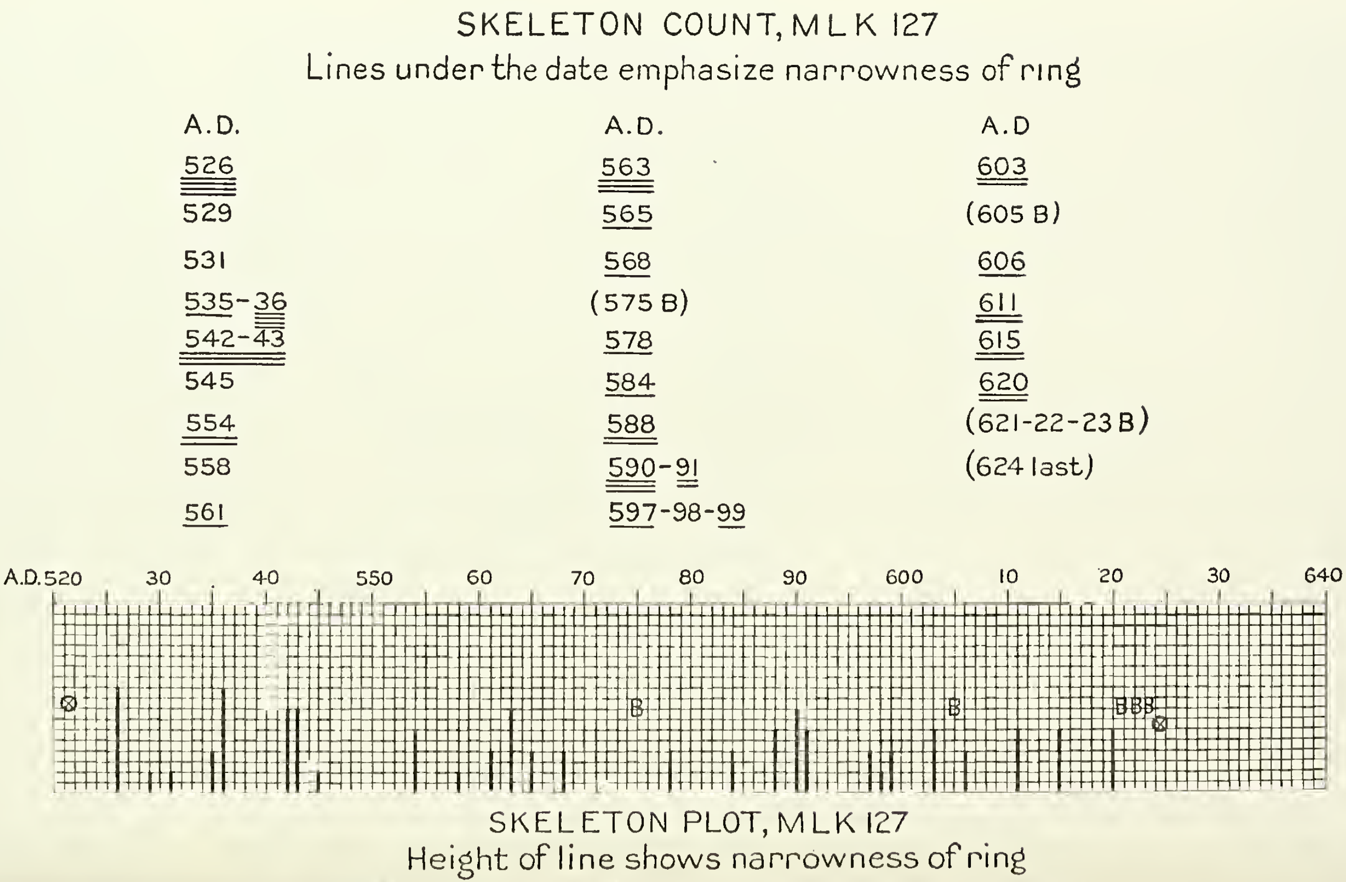


FIG. 10—Frequency distribution: ring widths in datable though not sensitive tree records.
e. Susanville, Calif., 1813–1931 (coll. by E. Antevs).
f. Central Washington, 1813–1931 (coll. by I. Bowman).

Dry years, however, reduce this source of differences between the trees and in Arizona become excellent points of agreement.

So the deficient rings from different trees may readily be compared in the field by this plot that skeletonizes the facts about a sequence. This plot merely requires a count outward from the central part and a note of the



SKELETON COUNT, MLK 127

Lines under the date emphasize narrowness of ring

A.D.
526
529
531
535-36
542-43
545
554
558
561

A.D.
563
565
568
(575 B)
578
584
588
590-91
597-98-99

A.D
603
(605 B)
606
611
615
620
(621-22-23 B)
(624 last)

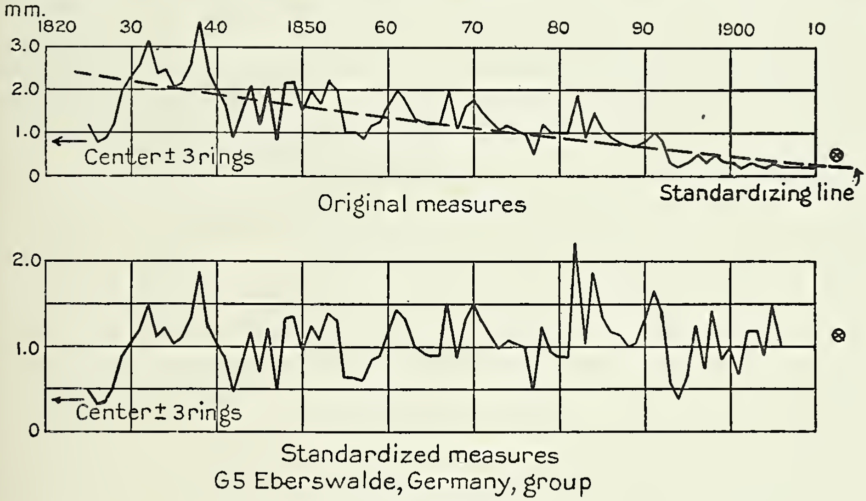
SKELETON PLOT, MLK 127

Height of line shows narrowness of ring

Fig. 11—Skeleton count and skeleton plot. See lower specimen in frontispiece.

small and microscopic rings. Extra large rings and frost or other injury effects are noted also; they sometimes help. A standard time scale is prepared along a horizontal axis, and the deficient rings are marked in their proper relative places, with solid ordinates made longer and longer as the rings are found more and more minute or absent. It is usually very easy by comparing two such plots to test cross-identity in two trees and show whether they were living trees at the same time. Of course, one of two plots compared may represent a well-established chronology with its dates all known, and the other may be from a log picked up in an ancient ruin.

Mr. H. S. Gladwin, Director of the Gila Pueblo at Globe, Arizona, felt that too many rings were omitted in this form of plot and has proposed an increment plot that promises to be of important use. The increment from each ring to the next is measured and inserted on the usual time scale in two colors; pluses are one color and minuses are another, and such colored lines are proportional in length to the increments. Thus nearly every ring is represented. Averages may be taken and variable rings sometimes have two colors on them. Cross-dating by this method becomes very strong. Its successful application is even more dramatic to the student than the ordinary skeleton plot, but its field use is curtailed by the need of measurement.



Original measures

Standardized measures
G5 Eberswalde, Germany, group

FIG. 12—Standardizing.

Standardized curves are curves equalized or brought to a uniform mean value so that one tree record with large average growth shall not dominate other records of small mean growth. If, for example, we have ring records that differ greatly in mean ring size and if we plot the record of each tree separately and analyze it for cycles, we shall find the cycles existing both in the small-growth records and those in the large-growth records as well. But if we average the curves together and analyze the mean, we get the cycles in the large-growth records and lose some or most of those in the small-growth records, because in fact, so far as cycles are concerned, the various curves have entered the average with weights proportional to their mean sizes. Hence in practise, to combine curves for cycle analyses we must bring them to the same mean value, which for convenience is unity. (These curves, it will be remembered, represent departures from a zero line and not from a mean.) This process is easily done by reducing each curve to percentage departures from its own mean; that is, each separate value is divided by the mean of the curve. This brings the new mean of each curve to unity, and variations expressed in percentage give an illuminating view of what is happening in the curve. The average of the equalized curves gives equal importance to the variations of each curve and is in proper form for analysis.

There are further points for consideration in this usage. When a tree ring is absent and its measure goes to zero, that value tells something important, but whatever it tells is greatly exaggerated. Again, when we examine the shorter cycles going on near a minimum of a long cycle, such as short cycles in monthly sunspot numbers at minimum of the 11-year sunspot cycle, variations from a mean fail to tell the story. Thus we reach the need for local equalizing within a curve, which is a more difficult task but absolutely necessary if we are to get the cyclical facts. In the case of trees, we are trying to find the variations common to many trees in identical dates over a large area. Obvious idiosyncrasies in individual trees must be removed if each tree is to contribute its best to the common result. The western yellow pine is an isolated tree and its early rings are very thick to build a framework and give it strength. The change in mean ring thickness with age is called the age curve. Douglas fir and pinyon usually begin under protection of other trees, and their early rings are small and grow larger before beginning to diminish regularly with age. These different age curves are easily removed by plotting each tree record and drawing the apparent mean age curve as nearly straight as possible through it. This mean line or age curve is called the standardizing line and at each abscissa is divided into the corresponding measured ordinate to produce the standardized value.

The standardizing line is drawn only by someone of much experience. It is made straight or with an irreducible minimum of curving or bending so as to avoid inserting or taking out any cycles. A curve with such line is shown in figure 12 together with the effect of standardizing. The process of standardizing has received specially careful application in connection with very long curves in order to disclose long cycles if present. The methods developed will be described below under compressed curves.

The big sequoias are in rare cases subject to "gross" rings or a limited succession of rings of greatly exaggerated thickness. They are best examined on top of a stump and may be due to a strain or fire injury and a vigorous effort of the tree toward recovery. The growth curve of a sequoia becomes far more normal when such gross rings are greatly diminished by moving the standardizing line upward. Complete removal, however, is never practised.

These gross rings are very rare in a measured sequence because they are easily seen on the stump and the radial cut from the stump is selected to avoid erratic growth. Obvious fire or pest injuries or intervals where the rings could not be correctly identified are excluded from the record.

Merging occurs in parts of almost every group average. The several trees whose growth curves are to be combined usually end at the same time, perhaps in the very same year, but the beginnings extend over a long interval. One or two curves may begin a hundred years before the others. The shorter curves must be entered without producing fictitious maxima or minima. The common method of treatment is to make a plot of all the individuals on a large scale for several years before and after the merging point. Such a plot is shown in figure 13. An incoming or an outgoing curve then easily shows whether its terminal values are in accord with the other tree records. If only one or two terms are discordant they may be omitted. If ten or fifteen terms are involved, the curve considered has its final 9 values (beginning or end, as the case may be) weighted in a diminishing scale from 0.9 to 0.1 ending at the final term with the weight of 0.1. Then an average by weight merges the new curve into the group without any jar. In rare cases a series of 20 has been used for merging.

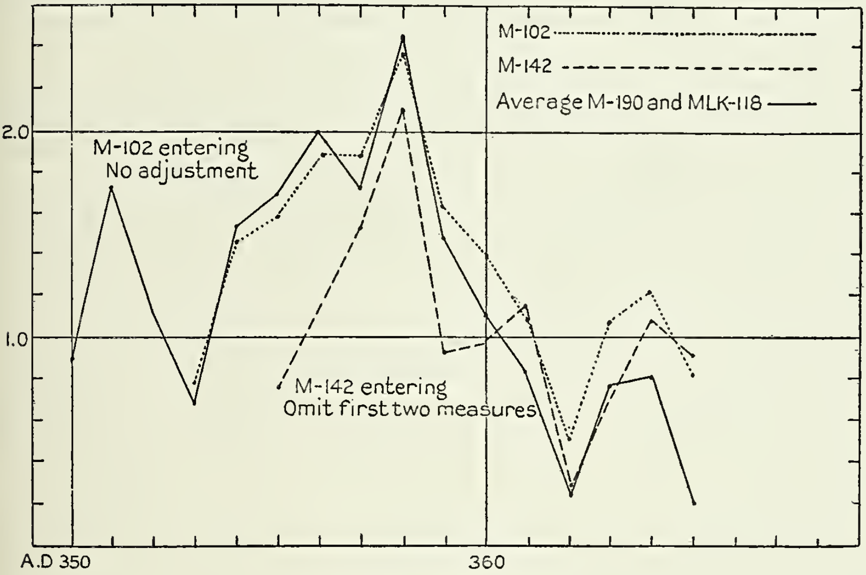


FIG. 13—Merging diagram.

Technique of Long Records—The writer has been fortunate in developing two accurately dated long ring records having climatic significance, one of 3200 years in the big sequoias of California, and the other of 1900 years in the pines and firs of the Colorado Plateau, chiefly in Arizona and New Mexico. Consideration of the best form for the expression of such data will appear in a later chapter. Some features of that consideration are very general and may be stated here.

The sequoia curves are continuous records. Weak and defective records had to be eliminated and occasionally some merging had to be done. But the plateau pines of Arizona and New Mexico have relatively short records. They show maximum length of a little over 500 years and a common length of less than 200. Hence typical records that were exceptionally long became very valuable and much dependence has been placed on them. In spite of these the number of mergings is large in the Arizona records. This is not all a loss; each "joint" has had years of careful consideration; that means in many cases a holding back of the results for years until the evidence was convincing. Such care was considered worthwhile with the plateau data because they approximate rainfall records so closely.

Compressed Curves—Long records give a unique opportunity of comparing cycle data from two separate geographical locations; they permit the study of short cycles back in antiquity, but more especially they give us a chance at cycles a century and more long. Adaptation had to be made of these very long curves to the capacity of our analyzing instrument which can handle 400 or 500 terms at a maximum. Again 30 to 40 years has been the maximum cycle length adequately analyzed in curves plotted on normal scale of 2 mm. to the year. Hence the long curves have been "compressed" into shorter lengths; that is, the time scale has been reduced so that longer cycles would come within the capacity of the instrument. Different tests have been made for effecting this compression, such as smoothing, taking means of 10, means of 5, overlapping means of 5. Since our minimum cycle seen on the instrument is 5.0 units, simple means of five years, not overlapping, have come to be our usage.

This should not be done on standardized values because of the danger that standardizing, although not affecting short cycles, could more easily influence long cycles; it must be done on the original measures of each individual tree. Five-year sums so made are plotted and standardized anew for each individual tree and averaged together in a new group table. These new curves then either for individuals or for the group offer a cycle range of 25 to 150 years or more. To get yet longer cycles, we again go back to the original measures and gather the 5-year means into new groups of 5, standardize them individually, merge and average them to get cycles between 125 and 750 years or more. That is perhaps all we are justified in trying to get from our long curves.

Curve Character Figure: Mean Sensitivity—Mean sensitivity is the mean percentage change from each measured yearly ring value to the next. It uses the reading from a base and can not be obtained merely from a series of departures from a mean. It is an important character in cross-dating and therefore has a climatic significance, telling us essentially which curves are presenting climatic data in the simpler terms. Low sensitivity occurs in the presence of abundant and lasting water supply; high sensitivity results from its scarcity. It is evident that we have here a character figure for tree-growth curves containing important information regarding environment.

Correlation Coefficient—The popular method of expressing relationship between two curves is the correlation coefficient. This is in essence the ratio between the algebraic sum of the products of corresponding residuals (departures from a mean) and the square root of the product of the sum of their respective squares. It may be written:

$$r = \frac{\Sigma xy}{\sqrt{\Sigma x^2 \cdot y^2}}$$

Thus it may be stated as the average product of residuals divided by the square root of the product of their average squares.

In the correlation coefficient the values are taken as departures from a mean or as "residuals." It makes no difference where the zero point is; for instance, one set of residuals may average three times as large as the other. One set of increments from each term to the next may be three times as large as the other, and no change is produced in the coefficient. In tree-ring work, this overlooks important features, for cross-identification depends on large increments as compared to ring size and fails with small increments.

The similarity between two trees curves then is only partly expressed by a correlation coefficient. The reliability of a bit of cross-identification may be estimated at over 90 per cent when the correlation coefficient is below 50 per cent. Complacent curves may show high correlation coefficient with doubtful cross-identity. In general, however, they are not far apart.

We have made various attempts to hit upon an index of similarity that is more satisfactory than the correlation coefficient. Dr. Glock has used a "trend coefficient" reached by dividing the sum of the positive products of corresponding increments from two curves by the sum total of positive and negative products disregarding signs. This is easier to compute than the correlation coefficient, but here again one set of increments could be increased or diminished in a definite ratio without affecting the result.

A simple trend comparison, occasionally made use of by ourselves and others, is the percentage of cases of agreement in rising or falling value of the increment. It gives a fair idea of similarity.

One of the best devices is the scatter diagram using original values from zero and arranging the vertical and horizontal scales so that the mean values of each curve come near the center of the diagram and the zeros come at the lower left corner. This arrangement appears automatically if each curve has been standardized; in fact the comparison is usually made between standardized curves. Departures from a mean may be used with equalized average residuals.

The diagram resulting from such plotting of standardized curves gives a ready and vivid picture of the points of similarity between two curves by the shape of the cloud of dots, especially its departure from the circular form along the diagonals. Three factors are really needed to give the result: the ellipticity of the dotted area, the semimajor axis, and the direction of the major axis. (See page 91 for discussion of an example.)

Periodogram—The periodogram is a summary of cycles found in a series of data: the cycle lengths are commonly expressed along the axis of x between limits that are evident. The ordinates decide the type of periodogram. In Schuster's original form they were derived from amplitudes of the sine curves involved in the analysis. Dr. Alter has used the name correlation periodogram as applied to the curve of correlation coefficient values obtained by comparing a curve with itself at lags of 1 year (or unit), 2 years, and so forth, up to about half of the total number of terms.[1] With the large number of cycles obtained in many curves of considerable length, we find it very convenient to use a diagram showing the number of occurrences of the various cycle lengths: this is called a frequency periodogram. When this frequency is determined separately for successive intervals of time as for successive centuries, we are calling it a "progressive" or chrono-periodogram. (See figs. 21 and 55.)

GRAPHIC EXPRESSION OF CYCLES

Cycle Integration or Summation—This has been the fundamental method of testing for cycles in any succession of data. It consists in placing successive blocks or sets of data one under the other, each just containing the cycle length. To illustrate—suppose we have a series of values of sunspot data (smoothed annual mean numbers, neglecting the fractions) as follows:

We can test for a 10-year cycle by adding and averaging the columns as they stand, and as a result we find no cycle of any consequence (see fig. 14*a*). But we see in table 1 that the data have a somewhat suggestive distribution with the larger numbers moving to the right in each successive set, and to see it better we plot figure 14b in a crude quantitative distribution and pass an estimated line through the maxima. If the best solution were 11 years, the line of maxima would slant to the right 1 year for each decade. It does more than that, for it changes to the right about 3 years for each 2 decades. That gives us a double value in 23 years, or 11.5 years as a rough solution.

Now if we wish to integrate these data on an 11.5-year period, we do it by the following approximation, which is accurate enough for our purpose, namely, to plot a fairly good average of the sun-spot cycle from 1833 to 1924.

With this table before us we realize how much extra trouble it is to rearrange our numbers for testing each proposed cycle and especially to test a fractional cycle, or one that does not consist of an even number of units. This fractional test is especially irksome because the values really should be interpolated. We could do all this very easily if we could make the additions at any desired diagonal direction, including those giving fractional periods,

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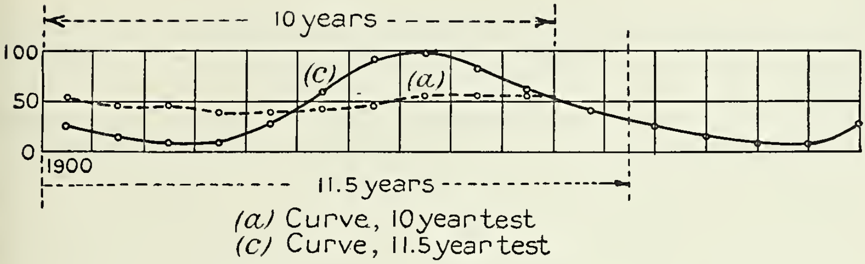
[1] Dr. Alter is now using a simpler coefficient in forming a periodogram, see Bibliography, 1933 (3).



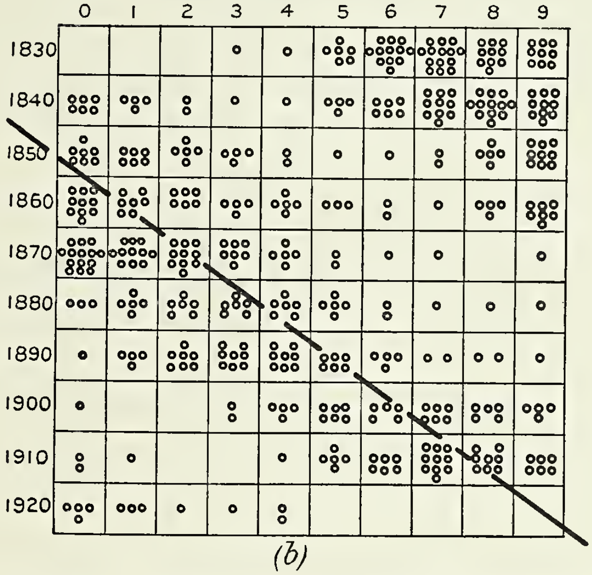


FIG. 14—a. Summation (integration) curve of sunspot numbers at 10.0 years.
b. Graphic representation of integration table.
c. Summation curve at 11.5 years.

TABLE 1

	0	1	2	3	4	5	6	7	8	9
1830	...	...	...	8	13	57	122	138	103	86
1840	63	37	24	11	15	40	62	98	124	96
1850	66	64	54	39	21	7	4	23	55	94
1860	96	77	59	44	47	30	16	7	37	74
1870	139	111	102	66	45	17	11	12	3	6
1880	32	54	60	64	64	52	25	13	7	6
1890	7	36	73	85	78	64	42	26	27	12
1900	10	3	5	24	42	64	54	62	48	44
1910	18	6	4	1	10	47	57	104	81	64
1920	38	26	14	..	..	..	..	..	..	..
Sums	469	414	395	342	335	378	393	483	485	482
Averages	52	45	44	38	37	42	44	54	54	54
							Mean	46.4		

without having to rearrange or interpolate the numbers. This very need caused in 1913 the construction and use of the cyclograph to be described shortly.

Integration has its dangers and may be deceptive. Just as above in averaging curves together into a group, the curves must be equalized or standardized or one may dominate to the exclusion of the others, so here we are in fact averaging curves together into a group, and a strong configuration in one block of data may produce a cycle that exists nowhere but in that one block.

Since this type of integration is the basis of all mathematical forms of cycle analysis, its dangers have been well seen and various protections have been devised; for example, a common safeguard is to separate the data into two halves and see if the cycle comes out equally well in each half.[1] Such a process applied by Schuster in 1906, in his classical work on the sunspot numbers, made him see at once that there are other periods in those numbers than the well-known one near 11 years.

TABLE 2

	1	2	3	4	5	6	7	8	9	10	11	1/2
1830	..	..	..	8	13	57	122	138	103	86	63	
	37	24	11	15	40	62	98	124	96	66	64	54
1853	39	21	7	4	23	55	94	96	77	59	44	
	47	30	16	7	37	74	139	111	102	66	45	17
1876	11	12	3	6	32	54	60	64	64	52	25	
	13	7	6	7	36	73	85	78	64	42	26	27
1899	12	10	3	5	24	42	64	54	62	48	44	
	18	6	4	1	10	47	57	104	81	64	38	26
1922	14	6	17	..	..	..	..	..	..	..	..	..
Sum	191	116	67	53	215	464	719	769	649	483	473 12	
Average	24	14	8	7	27	58	90	96	81	60	39[1]	

[1] If the extra half-year is placed at some other point in the cycle, the result is practically the same.

Thus integrations of selected values fall far short of giving satisfactory cycle analysis. Not only should each proposed period be tried separately in all parts of the data, but all nearby period values should each be tried throughout the data. We believe that our method described below is the only safe one yet suggested that fills these exacting requirements.

Successive Integration—In harmonic analysis a definite interval of time, usually the full length of the data, is taken as a fundamental, and integral parts of this, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, etc., perhaps to 30 different fractions, are taken as successive periods on which the data are summated, and the qualities of the resulting means ascertained. This is multiple integration applied in an effort to reach all possible periods that may exist in the data. But while this process covers many possibilities in short period lengths, it leaves large gaps in the longer period lengths. Suspected long periods are often sought by integrating several successive values from decidedly less to decidedly more than the suspected length and observing whether the cycle amplitude in the plotted means increases to a maximum and then falls away, as in figure 16. This is called successive integration and can be made very effective over short ranges.

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[1] For a cycle that is permanent, this test is very helpful, but for discontinuous periods it is obviously of little value.

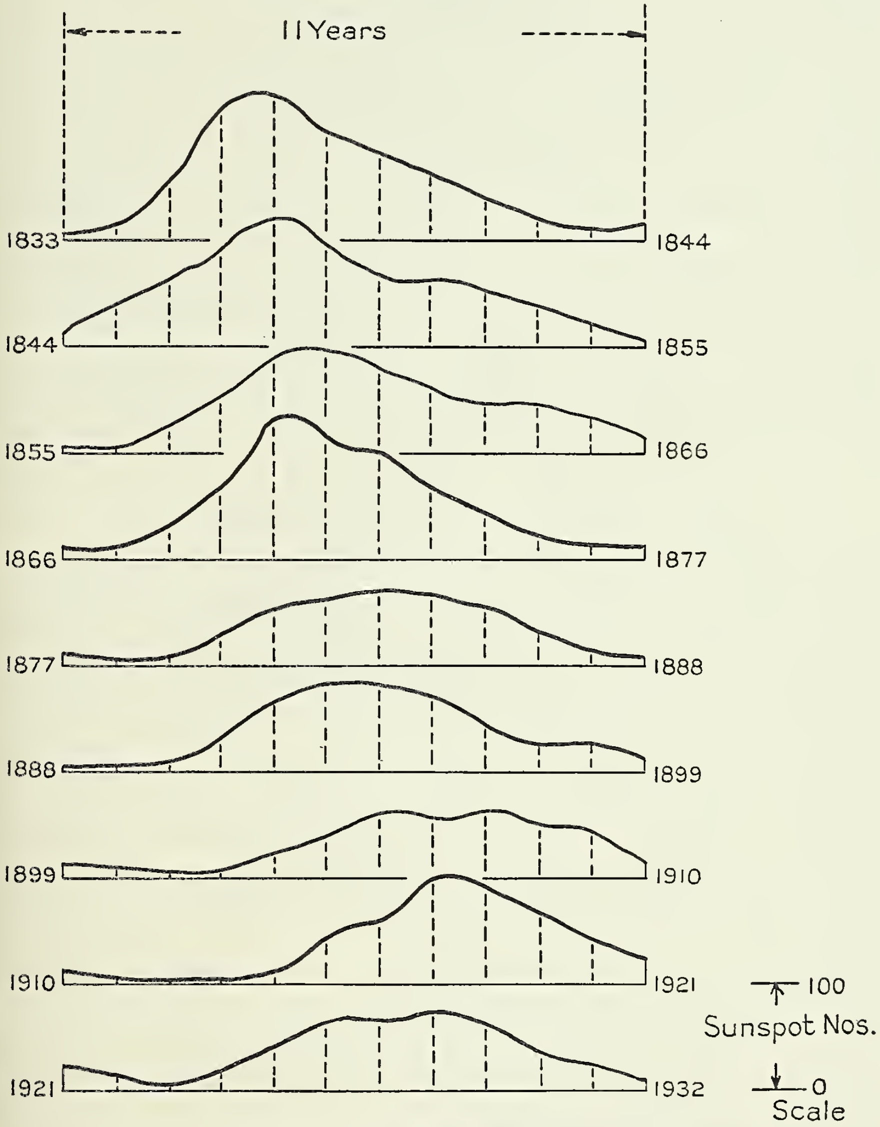


Fig. 15—Plot of sunspot data to show changing place of 11.4-year maxima in successive 11-year intervals.

Chrono-Integration—The successive integration above described deals with successively increasing cycle values as tested in the same data. Chrono-integration means a series of tests of the same cycle lengths applied in definite successive intervals of time. This process was used in connection with the first attempts at cycle analysis of our long chronologies (Chapter VI, page 121),

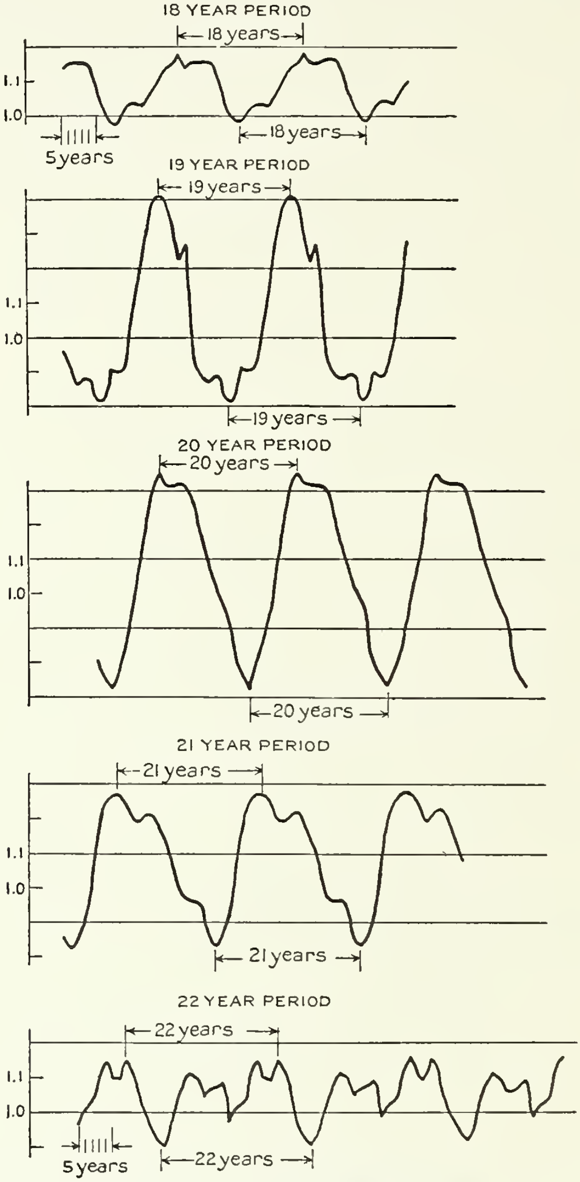


Fig. 16—Successive integration of FAM (Flagstaff area mean curve), 1700–1920.

to verify or deny certain changes in an 11-year cycle observed in a cyclogram. In carrying out this integration, the 500-year curve was divided into blocks of 57 or 68 years (or 69 years) and these intervals integrated at 11.4 years. (The results are shown in figure 33 of Volume I, page 103. See also Scientific Monthly, December 1933, page 491, fig. 12 and our fig. 52.) In this manner certain resemblances between climatic cycles in tree-ring growth and solar changes were first observed.

This chrono-integration method of studying cycle history was then applied to the long records of the giant sequoias in similar blocks of 57 or 68 years, but no especial result was forthcoming. Integrations at 23 years, however, brought results that seemed to show frequent division of 23 years into a small number of integral parts. This in turn led to "overlapping integration" at 23 years, which has seemed the most successful method yet tried. In effect, this process consists in taking running means of three 23-year intervals.

The defect hitherto existing in this overlapping integration is that only one cycle length is tested in a very long series of integrations and other cycle lengths go untested. The difficulties of testing all cycle lengths as in common cycle analysis have been overcome in a process called "lag" analysis (see page 50).

PLOTTING UNSTABLE AND MIXED CYCLES

We shall find in a few pages that our analyzing instrument called the cyclograph (whose automatic pattern is the cyclogram), in its common visual operation combines successive integration (by the moving mirror) with chrono-integration (by retaining a time element in the pattern). This is accomplished by an "optical correlation" (as named by Dr. Alter) combined with a certain method of plotting unstable and mixed cycles. In showing a procession of discontinuous or short-lived periods on common rectangular coordinates, we have a time scale horizontal as usual and upon this we may plot cycle lengths as ordinates, as in figure 17a. But this fails to show a continuity that is characteristic of cycle sequences. If, however, we abandon the ordinary use of an ordinate scale for cycle lengths and combine a polar scale for cycle lengths with a horizontal time scale, we can show continuity with instability and even the presence of additional fragmentary periods. In this plot directions vary with cycle length as shown in figure 17b which obviously presents an 11-year cycle from 1500 to 1650, a 10-year cycle thence for a hundred years, and again an 11.4-year cycle from 1750 to 1900. There is also expressed the presence of an $8\frac{1}{2}$-year cycle in the early part of the 400 years and a 14-year cycle in the last hundred years. Thus we can see clearly that a combination of polar and rectangular coordinates gives a facility in expressing unstable and mixed cycles, of which we will make further use.

CYCLOGRAM PRINCIPLE

We find it more advantageous to make use of a method of plotting cycles that does not involve two different systems of coordinates but which brings the same effect in the plot. It can be developed easily by a series of very simple graphic transformations. Figure 18a gives an approximate sunspot curve on a horizontal time scale. The first transformation consists in splitting up this curve into 10-year blocks and placing one under the other, as in figure 18b, at definite and equal vertical intervals. Each block is extended beyond the ten years to 20 years or more. The dotted line A-B-C represents the same instant of time in three different blocks. The second transformation consists in swinging this line A-B-C so that it becomes horizontal, as in figure 18c, without changing the horizontal scale of figure 18b; that is, each plotted point in the diagram moves downward vertically and not on an arc. By this transition we secure a correct vertical time scale on rectangular coördinates. For convenience in use, this diagram as a whole is now rotated 90° to bring the main time scale horizontal, as in figure 18d.[1] This produces a complete time progression from left to right on rectangular coordinates. The vertical scale, which was the horizontal scale in b, expresses residuals from 1840, 1850 which are multiples of 10. It could be shown by trial that the exact multiple of any other convenient number could equally well be used.

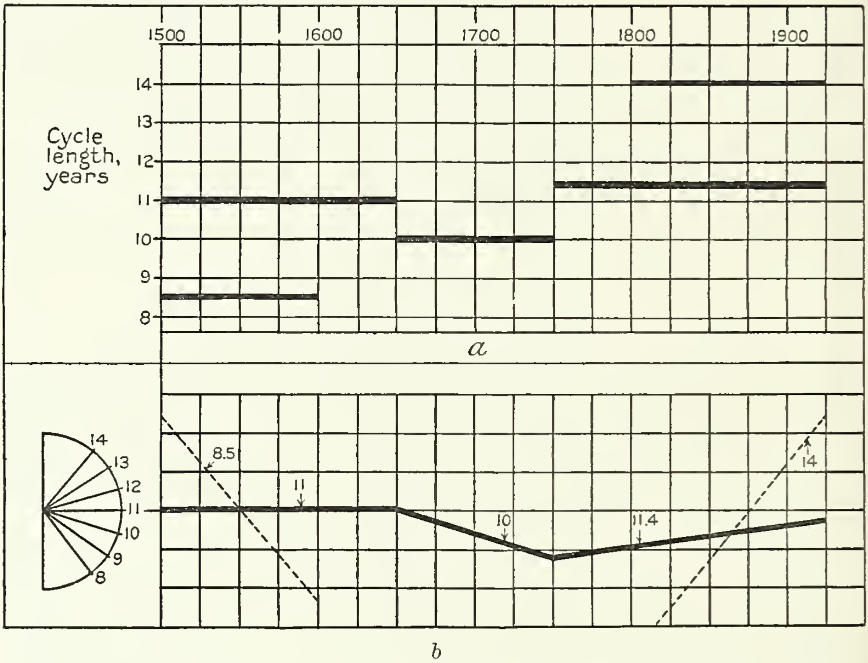
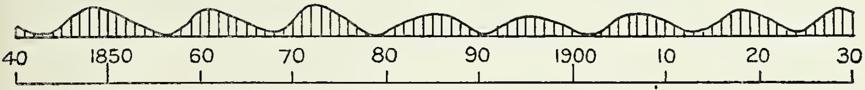


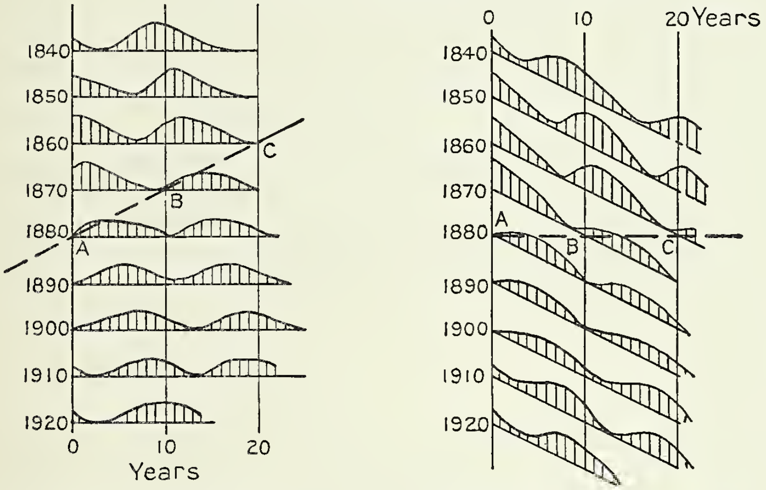
Fig. 17—a, b. Two methods of plotting cycles. Above, rectangular plot; below, combination of rectangular and polar plots.

[1] This change in representing cyclograms is apparent in the different position they hold in *Climatic Cycles and Tree Growth*, vol. I, Plate 12 (1919), and vol. II, Plate 9 (1928).

In the diagram 18d we have reached the plot we have been seeking, but the original ordinates of figure 18a, consisting of sunspot numbers, become meaningless in the new position and are therefore swung up into a vertical position perpendicular to the page, as in figure 19a, and must be expressed as a third dimension, which is easily done by representing light intensities by local enlargement or by some half-tone process as in common photographs. Thus all maxima in the original data are retained in the plot.

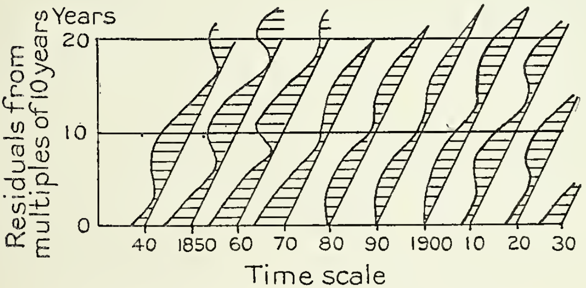


a Common plot of sunspot numbers



b The same divided into 10 year blocks

c Last figure changed to rectangular coordinates



d Last figure rotated to bring chief time scale horizontal

FIG. 18—a, b, c, d. Cyclogram demonstration.

This is crudely represented in figure 19a. Here, as stated above, we have the main time scale horizontal and a vertical time scale consisting of residuals from 10-year multiples. We note here that if we take some date such as 1845 and in its proper place on the horizontal axis give it an ordinate of 5 years from 1840, we also plot it at 15 years as a residual from 1830 and at −5 years as a residual from 1850, and so on for a number of repetitions in a vertical line. Thus we build a pattern that repeats itself. This gives a chance to see other cycles beside the one being plotted.

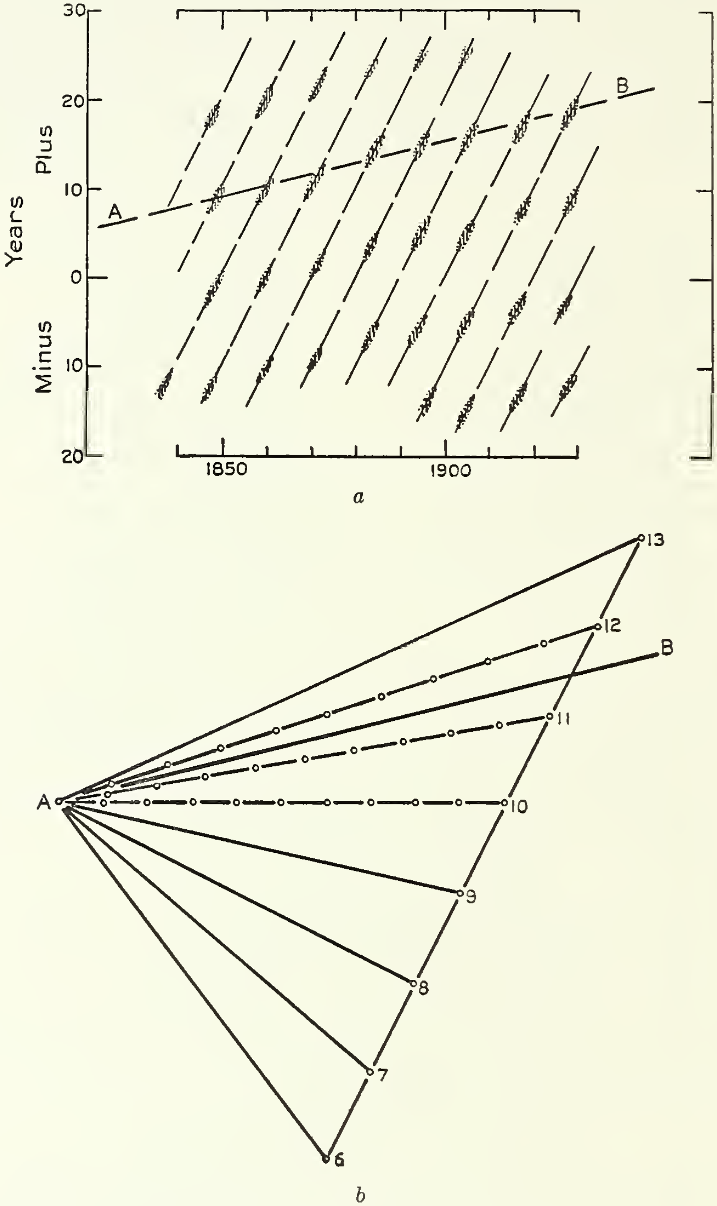


Fig. 19—a, b. Cyclogram demonstration, second part.

In this diagram the alignment of the maxima along the direction A-B becomes very prominent, much more definite than it showed in previous figure 14. We can investigate the meaning of the directional character of that line by figure 19b. This diagram, as is evident, is prepared on the coordinate system of 19a. Starting at any point, for example at A in 19b, we lay off the maxima of a 10-year cycle. We find that they produce a straight horizontal line as indicated. Now we lay off an 11-year cycle. This will be built up of 11-year intervals measured to the right on the main time scale and 1-year residuals set off upward on the vertical scale. Wherever we lay off an 11-year interval it will take a slant parallel to this slope as plotted up to the right. If we lay off a cycle of that length the maxima will form a straight line at that slant. A 12-year cycle produces maxima in a straight line at a still steeper inclination wherever it occurs in the data. Once started it becomes very easy to lay off a full set of directional values

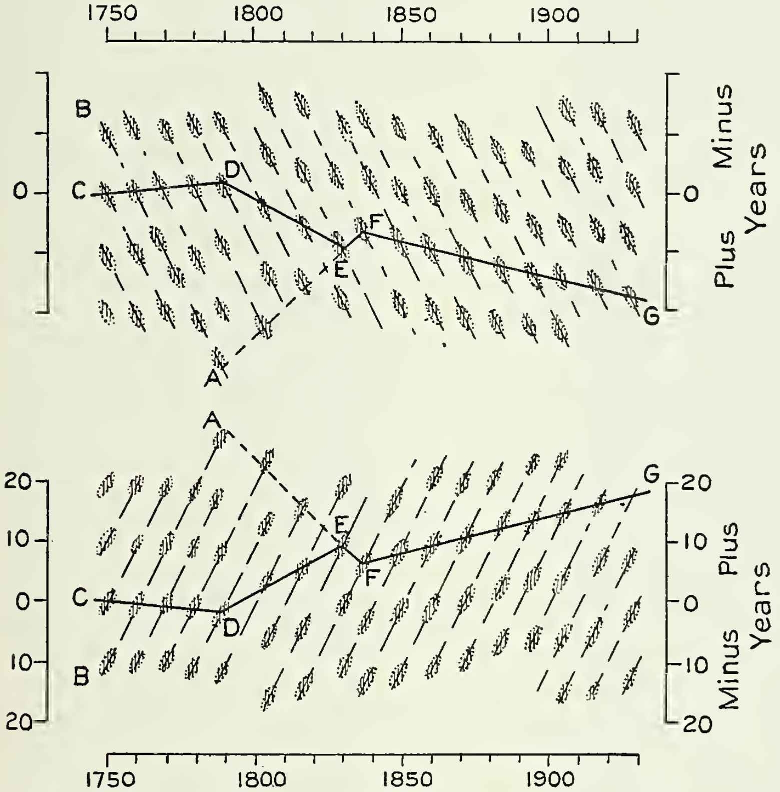


FIG. 20—Cyclogram plot of sunspot numbers, 1750–1930.
Note: if the analyzing lines A-B are made to slope the other way, the interference sequence CDEFG is inverted.

expressing cycle length between 6 and 13 years. We may now interpolate the particular slant shown by the sunspot maxima in figure 19a. By comparing it with our set of position angles just developed, we obtain an approximate solution of 11.4 years for the mean cycle length exhibited by the maxima since 1833.

Now on the same coordinate paper let us extend the plot of sunspot numbers back to the maximum at about 1749 and see what is indicated by the same method of solution. The plot is shown in figure 20 and we see that the various maxima instead of being scattered at random do form a broken line or a sequence of fragmentary straight lines. Since each straight line is a temporary period, we can, I think, consider the maxima sufficiently in straight lines to call this diagram a sequence of short-lived or discontinuous periods.

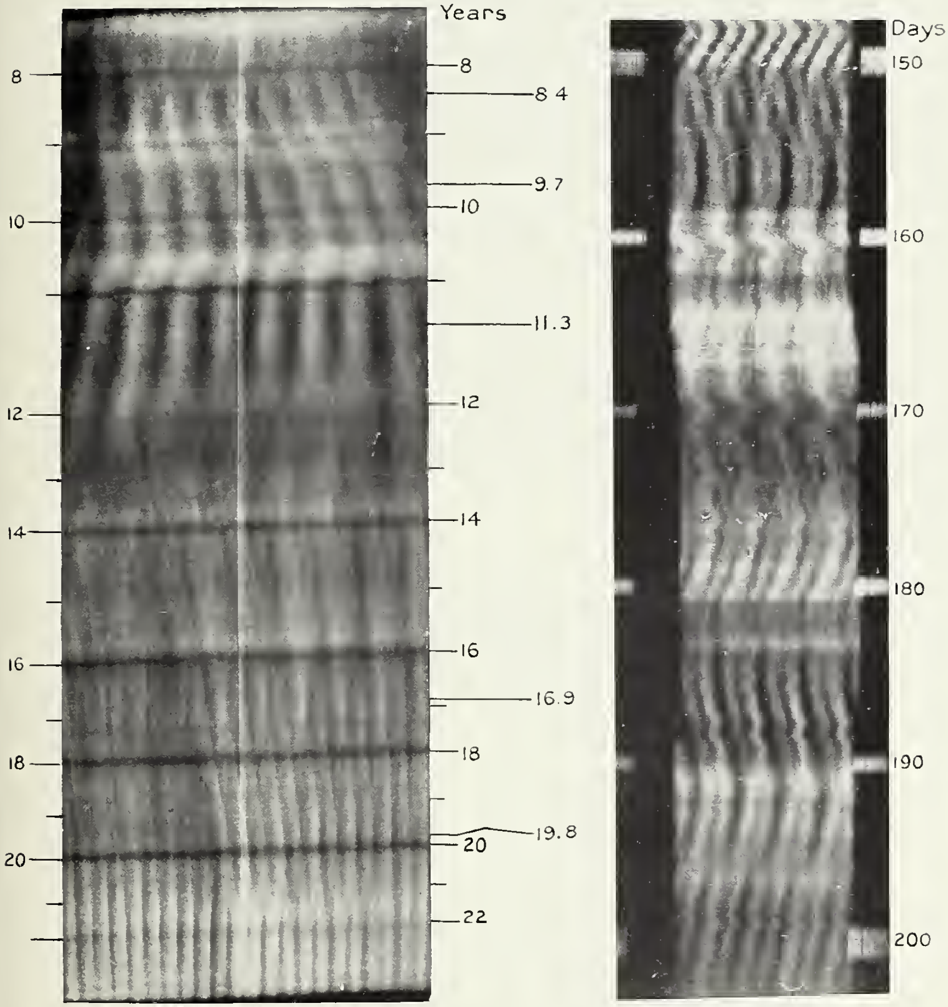
In our polar diagram of figure 19b made in the same coordinates, we have an easy solution for the approximate cycle lengths shown by these lines. If the polar plot is on transparent paper it is only necessary to superimpose it and we find as follows:

Cycle length from plot:		Cycle length from time interval:	
1750–1790.....	9.7 years	between 5 maxima 39/4 or	9.8 years
1790–1830.....	14	between 4 maxima 42/3 or	14.0
1830–1837.....	7	between 2 maxima	7
1837–1930......	11.5	between 9 maxima 91/8 or	11.4

It will be noticed that by means of the half-tones, all the original data may be represented in figure 19a and, if other cycles are present and sufficiently conspicuous, they will constitute alignments in other directions as indicated in 19b. It is evident that a given alignment does not necessarily continue through the whole pattern. If, for example, a cycle did not exist before some definite date but did exist after that date, we would find an alignment beginning at that time. (See Plate 16.) Thus we can study cycles or periods equally well, whether permanent or fragmentary, provided there are a sufficient number of repetitions. Thus the detection of the presence of a cycle is necessarily obtained in its full and extended form and not from integrations and the cycle must become evident in competition with a considerable range of values on either side which, if there, show at the same time. So a proper and careful selection of value can be made and the analysis is not in any sense a special test for a single value.

CYCLOGRAPH

Cyclogram analysis can be performed by anyone who has the patience to understand it. It has introduced new methods and results in cycle study, for fragmentary and interrupted periods can be measured as well as permanent ones. This gives a new and more efficient approach to climatic and sunspot cycles. The automatic character of this analysis has made it extraordinarily rapid. Thus five minutes at the cyclograph has often been enough to



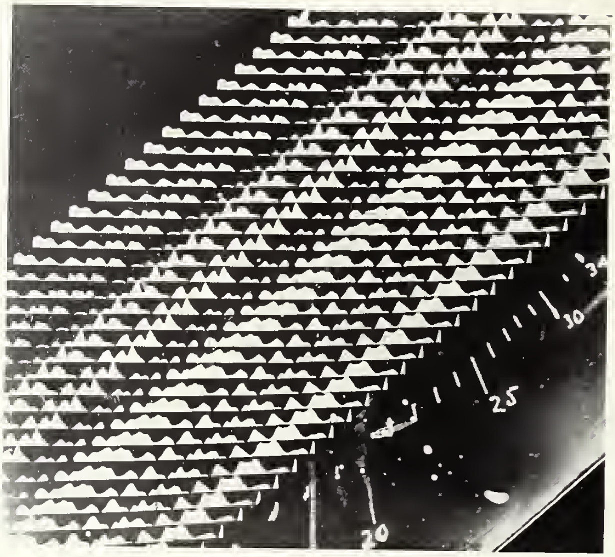
A

B

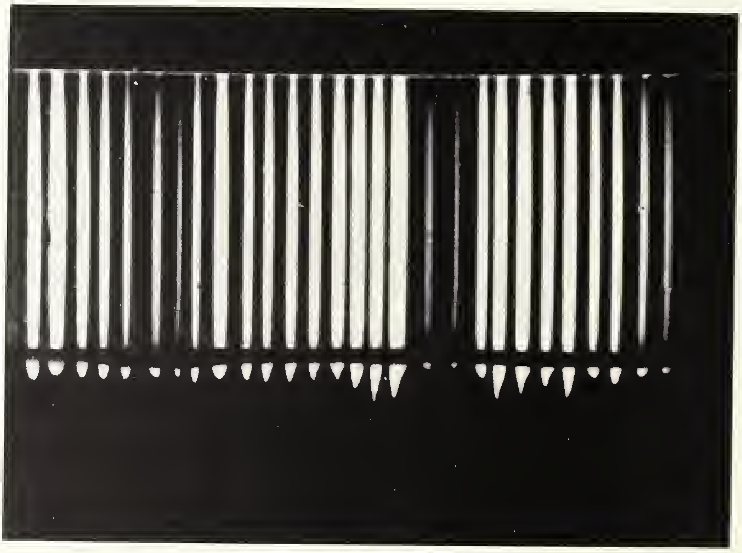
Periodograms

A. Periodogram (1913) of sunspot numbers since 1760.

B. Periodogram (1918) of variable star, R Arietis, showing period of 187 days (see Appendix).



A. Cyclogram by spectrometer process (1914).



B. "Sweep" or cylindrical pattern; the original plot, inverted, shows below the sweep.

measure and check all cycles within a length range of 5 to 40 terms in a curve showing 175 terms.

The efficiency of this form of analysis has resulted largely from the automatic production of the pattern called the cyclogram. The cyclogram may be described as an adjustable 3-dimensional plot[1] containing—

1. A general horizontal time scale.
2. An enlarged vertical time scale giving residuals from some convenient exact period such as 10 years. This procedure separates different periods into different straight lines pointing in different directions. In the mechanical plotting of the cyclogram this "convenient exact period" may be made to take successively changing values over a long range.
3. The original ordinates are changed into a third dimension and represented in half-tones by light intensities.

DEVELOPMENT OF CYCLOGRAPH

It was Schuster's work on the periodogram (fig. 21, page 42) that started our cyclogram type of analysis. The first step was a question: How can we perform quantitative integration in any desired direction other than the vertical? and the answer came at once, "By light intensities." So the "multiple plot" was tried in 1913 (see vol. I, *Climatic Cycles and Tree Growth*, Carnegie Inst. Wash. Pub. No. 289, 1919, Plate 9b) and its integration at continuously changing angle (in A of the same plate) by a cylindrical lens and a photographic plate moving across a slit.

The multiple plot was simply a pictorial reproduction of the integration table given a few pages back. The series of data was plotted many times in solid white on a black background. These plots were mounted one below the other at equal vertical intervals and between each repetition there was a constant horizontal off-set amounting to a convenient average cycle length, just as in the table. An integration of the light values in the vertical by a positive cylindrical lens with vertical axis summated any cycle that existed in vertical direction across the multiple plot. The integration was recorded on a photographic plate and measured for quantity of light. The whole multiple plot was rotated into a different angle and a new integration made in the vertical and another period tested. The movements of plot and plate were made continuous by clockwork.

A periodogram was thus produced (see Plate 12A), which indicates the presence of a period by breaking up into corrugations, since it is merely the merging of periodic maxima in the multiple plot. Volume I, referred to above, gives several periodograms in Plate 11. They are very crude but are part of the history. Except for these photographs and some tests on variable stars (in 1918; see appendix) the use of the periodogram was dropped after about 1916.

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[1] It may also be described as an optical, photometric mechanical plot produced automatically in a complete form from a prepared curve of data; in it the time displacement of any maximum from its periodic position is plotted at its observed time.

The multiple plot from which the periodogram was made was itself laborious to make, and a year's thought was put on the problem of producing it automatically (1913–14). Such diagram must consist of duplicate solid plots of the data, placed one below the other at equal distances and with equal horizontal off-sets from each to the next. A solid plot illuminated (later called cycleplot) may be seen in Plate 14, general view of the cyclograph. The first bit of progress was obtained by putting on an opaque background a transparent solid plot inclined at 45° slant in a window of a well-darkened room. Then a camera was mounted on a spectrometer plate and rotated a small angle each time between exposures. This gave a fixed multiple plot as reproduced in Plate 13A, and incidentally showed a 20-plus year cycle in Arizona trees. It was recognized at once that this told a story that could not be found in the periodogram, for it gave not only periods but their changes as time passed, $\frac{dp}{dt}$, and for a time it was called the "differential pattern."[1] This was still not a satisfactory solution and the transparent plot was the only part that survived to become an essential part of the final instrument.

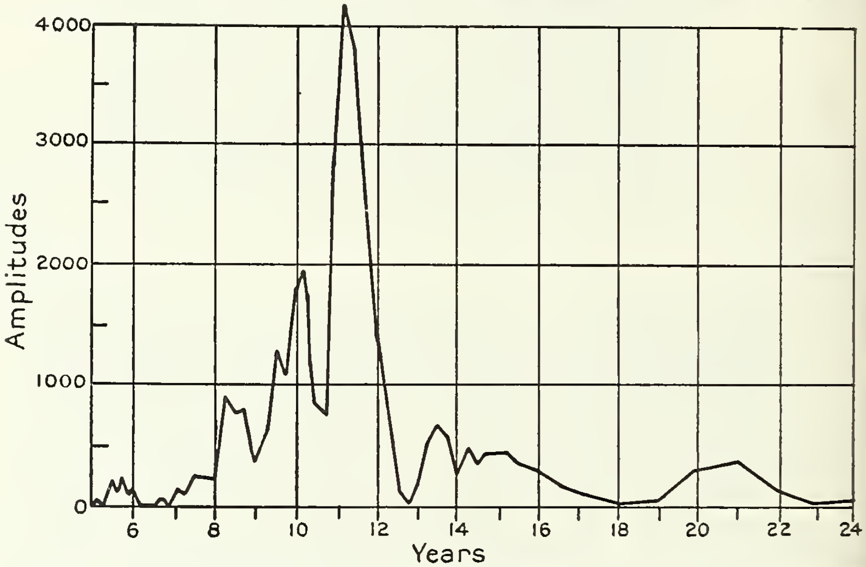

Fig. 21—Schuster's periodogram of sunspot numbers. Note: See also Stumpff's periodogram computed by Schuster's method, reproduced in figure 55.

The cyclogram is a chrono-periodogram or a periodogram differentiated with respect to time. The cyclogram was produced mechanically in December 1914 as follows. If a transparent plot is photographed with a camera having a positive cylindrical lens with its axis perpendicular to the direction of the plot, the resulting image consists of a bank of parallel vertical bands, each band receiving its light from a corresponding maximum in the curve and therefore its light intensity is proportional to the height of that maximum. This pattern was first called a "sweep" (Plate 13B, like the effect of a broom on a sanded surface) and later it was called the cylindrical pattern. If we cut across this cylindrical pattern in any direction with a straight line—for example, with a narrow transparent line cut in opaque paper—we find coming through this line a complete set of data, taking light intensities for ordinates. If now we take a large number of such transparent lines parallel to each other and equidistant, we shall find a perfect multiple plot coming through. Each separate line contains the full set of data, as far as its length permits, is parallel to its neighbors and presents equal offsets each to the next, throughout the whole pattern.

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[1] See Astroph. Jour., April 1915, p. 173.

So the basic parts of the cyclograph were established as a cylindrical lens in a camera and an analyzing plate made of equally spaced transparent lines placed just in front of the photographic plate. In order to read the cycles from a pattern so produced, it was necessary to measure the time scale of the image and the effective spacing of the analyzing lines and the actual angle between lines and bands. This was done by extra lenses and a small filar position micrometer. It was a real task to get the cycle length.

The trouble with any given cyclogram such as those produced in this way is that only a small range of cycle lengths could be found in it and therefore many other photographs had to be made. The range can be increased in several ways. Two of them have been tried and discarded; namely, rotating the analyzing plate and changing the spacing between its lines. The former added very little range and made the computation of cycle length a more difficult matter. We have called the latter a variable grating cyclograph. It falls far short of the method finally adopted in flexibility and produces confusion between fundamentals and harmonics.

The simple method finally adopted has all points in its favor. It produces results by changing the effective distance from the camera to the plot that is being analyzed, thus altering the scale of the image that passes through the analyzing plate. The change in scale becomes in effect a change in the cycle from which residuals are automatically plotted as described above in connection with the cyclogram plot. This change of scale is now done (since 1920) by altering the distance of a secondary mirror (see fig. 22) interposed between the transparent curve and the camera lens. Motion of this mirror by diminishing or increasing its distance from the camera changes in inverse proportion the size of the cylindrical pattern that falls upon the lines of the analyzing plate. The position of the mirror that by trial brings each definite cycle length into horizontal position (compared to a stationary thread in the field of view) is marked on its track and the instrument becomes in all respects a direct reading cycloscope capable of instant adaptation over a very large range.

The general arrangement of the cyclograph is shown in figure 22. The light from the illuminated curve, or cycleplot, is reflected in a movable mirror; it then returns to the camera which has in effect a positive cylindrical lens with vertical axis. The lens focuses the cylindrical pattern on an analyzing plate illustrated at 22b (and Plate 15A) whose transparent lines are inclined about 17° to the vertical. The geometrical relation of the parallel lines on the analyzing plate and the cylindrical pattern falling upon them are shown in figure 24, page 45. As the mirror moves, the size of the cylindrical pattern changes and rows of maxima coming through the analyzing plate look as if they were rotating about an axis. This is merely the change (almost instantaneous) from one "basic" cycle length to another (see Plate 15B; see also Appendix.

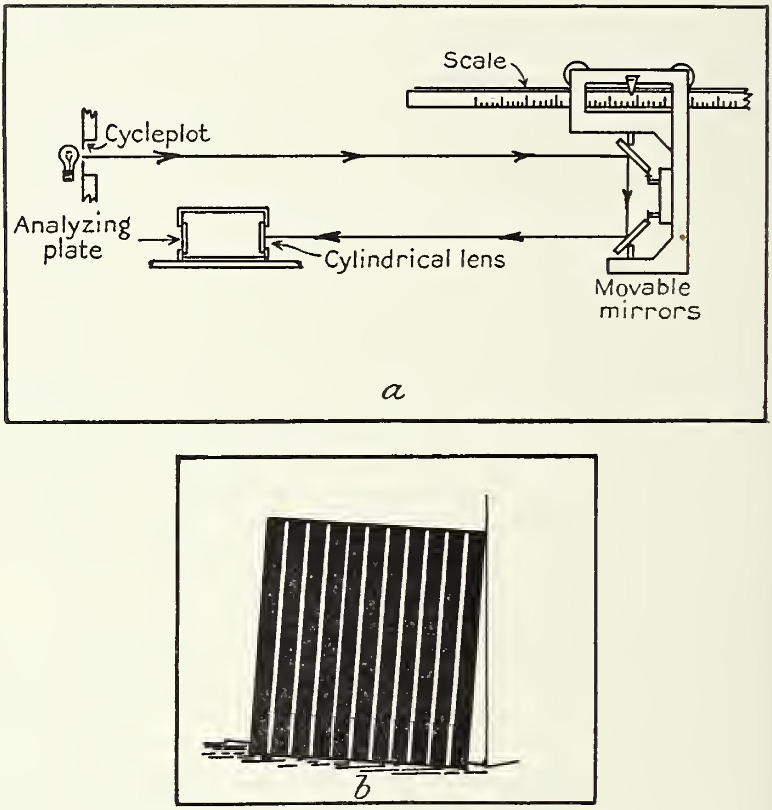
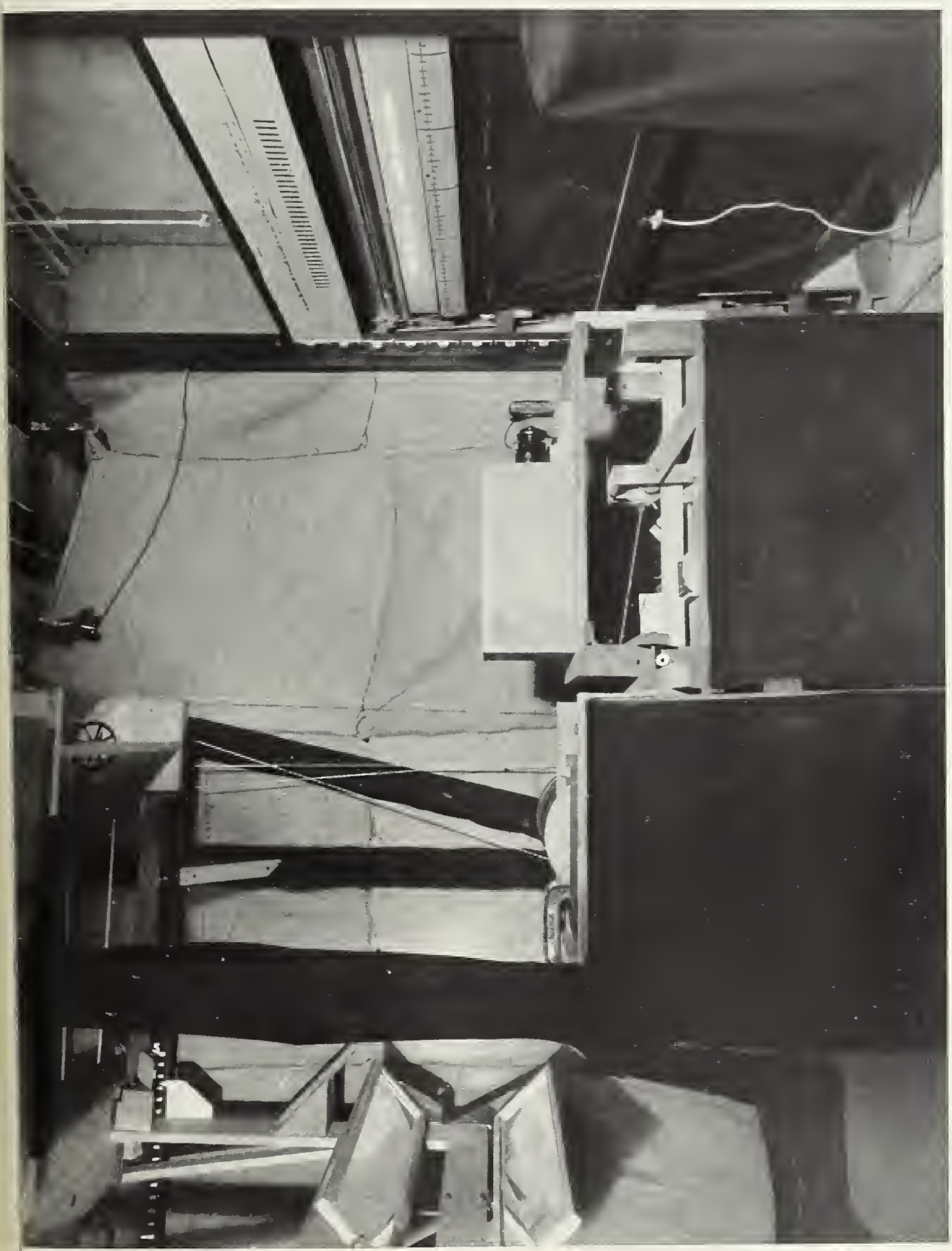
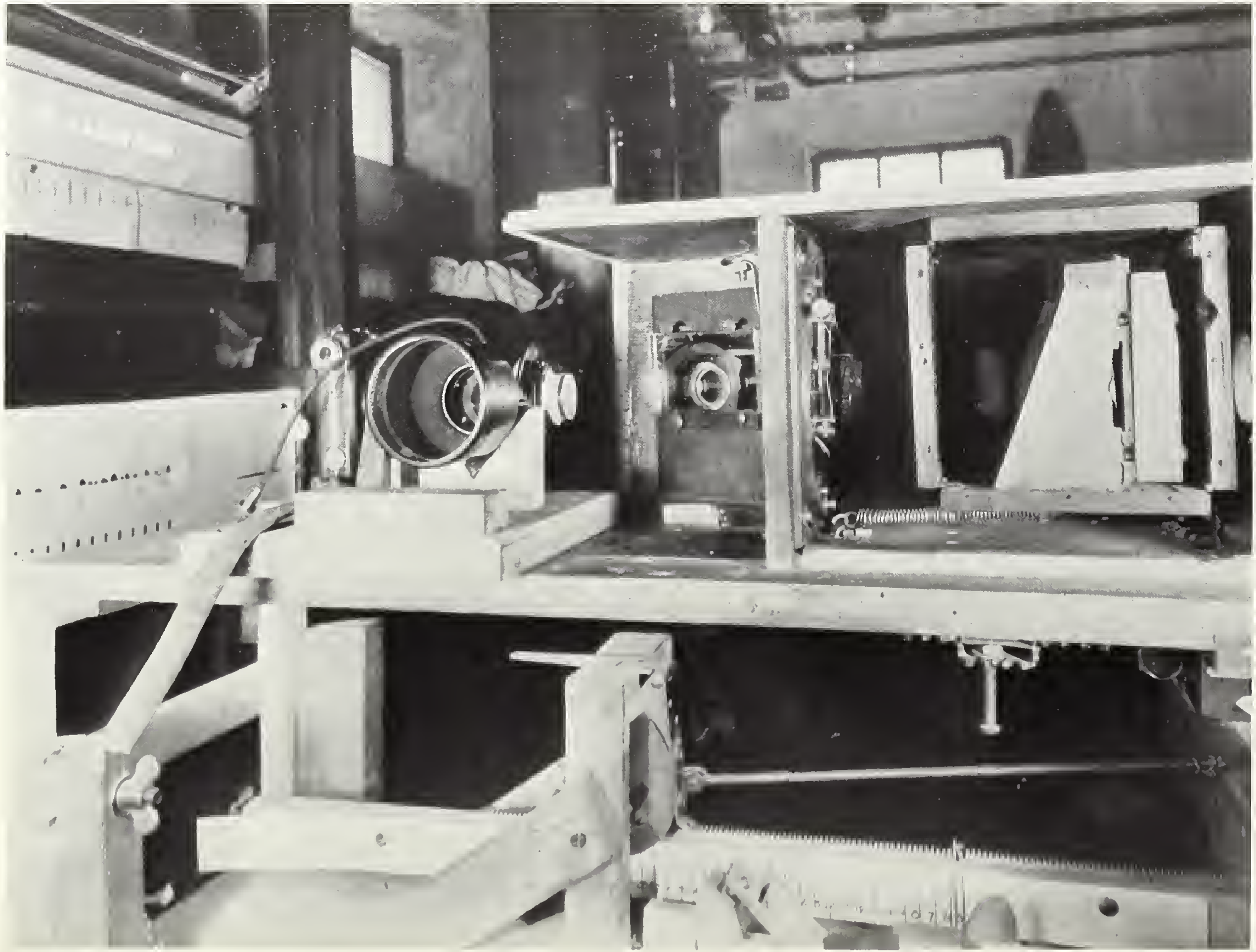


Fig. 22—Important parts of the cyclograph.
a. Schematic elevation.
b. Analyzing plate.

Cycleplots—Many improvements have taken place in the plots prepared for analysis. The original multiple plot was cut out of white paper and mounted on a black background. The first cyclograms in 1914 were made from a plot cut through black paper; tissue paper was placed over the openings and lights mounted at the back. A small photographic negative or positive of this was tried and found unworkable. The plot was then cut



The cyclograph. The movable mirrors show at left margin; the illuminator with cycleplot and rack show at right margin; the analyzing box is in center.



Analyzing parts of the cyclograph. Cycleplot at left edge; photographic attachment next and its reflection in a small viewing mirror; then partition holding analyzing plate; and at right the main lens suspended in a hinged square to permit automatic focusing, controlled by rod and spiral seen below.

through coordinate paper whose back was painted with opaque material. This was used in front of a long ground-glass behind which lights were placed.

The present process of making a cycleplot ready for analysis has the original data plotted on a standard scale coordinate paper whose smaller division, 2 mm., commonly represents one year. This plot is Hanned graphically and then the Hanned line is traced over carbon paper upon a strip of heavy brown paper 4 inches wide and some 48 inches long. A "cutting" line is marked in a nearly straight line along the minima and the maxima cut out above this line with a razor blade. In this way the maxima are sufficiently isolated so that they can easily be distinguished. If the original base at zero is used, too much light floods the pattern and the maxima are not distinguishable by the eye, as was the trouble with the patterns shown in Volume I (*Climatic Cycles and Tree Growth*), Plate 12.

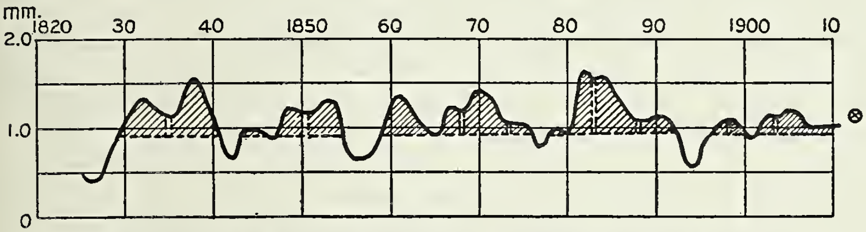


Fig. 23—Cycleplot, to show cutting line. Standardized tree growth, G 5, Eberswalde, Germany.

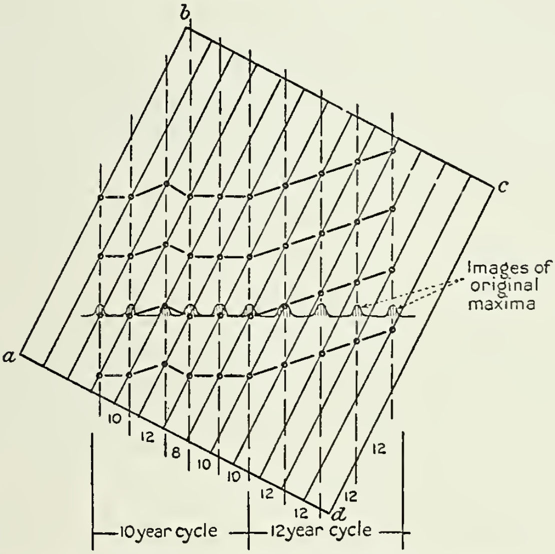


Fig. 24—The analyzing plate changes longitudinal displacement in position of maxima, to transverse.

A cutting line should be made as nearly straight as possible or it may confuse the analysis. This requirement was learned by experience. Certain analyses made before 1919 showed the Hellmann cycle, a two-crested 11-year cycle, very plainly (vol. I, Plate 12f). Analyses made early in 1932 failed to show it. A test on the early cycleplot revealed that a 19-year and even a 14-year cycle had been partly removed by a curved cutting line. To verify this fact the cutting line was transferred to a cycleplot, analyzed, and these two cycles were found in it. So, to extend the test, 19- and 14-year cycles were subtracted mathematically from the Flagstaff data and the Hellmann cycle was once more revealed. It is legitimate to remove cycles in the cutting line, provided the cutting line is itself analyzed to see what has been removed. In general analysis such usage is not advised, but in special cases this seems an advantageous way of removing interfering cycles.

A straight cutting line aids the evaluation of longer cycles by leaving them unaltered. The question of the cutting line then becomes a part of a larger practical policy dealing with the range of the instrument as to cycle length. The range extends from 5.0 years at the minimum to 30 or 40 years at the maximum. Beyond 40 years we replot at a compressed horizontal scale. At 30 years the visible cyclogram produced in the analyzing instrument is reduced in length to $\frac{1}{6}$ of its size at 5 years. Details are lost and the larger cycles become visible. Therefore we must make a cycleplot that is usable at each of these extremes. The nearly straight cutting line gives us the long cycles; then not to lose the short cycles, obvious minima not deep enough to reach down to the cutting line are joined to it by narrow "tongues" of opaque paper that are visible at short range but disappear at long range. One has only to try this to see that it does not distort the result. A cutting line with these details is shown in figure 23.

On the possibility that the cutting line had jeopardized correct analysis, many important curves were plotted again upside down and a new cutting line put in, encroaching this time a little on the maxima, and the minima were cut out and tested. This was not found to change the results and the cutting line procedure is considered satisfactory. It is evident that in this analytical process the centers of mass of the maxima become the important points of the plot whose periodic character is tested. In some cases the curve has been modified into a series of centers of mass and the resulting cyclogram becomes very brilliant and easy to read. In such cases, of course, caution is needed and results obtained in this way are taken as corroborations or suggestions (see cyclograms in Plate 15B).

The instrument as it stands covers considerable space; namely 6 or 8 feet in width by about 45 feet in length. The mirror is suspended from a track attached to the ceiling. The cycle scale is marked on the track after calibration by standard curves. Calibration readings are made in connection with every analysis. It is difficult to show much of this in any photograph but something of it appears in Plate 14 A and B.

Moving Rack—Many attachments to the cyclograph have been tried, including moving picture devices, but the one that has proved its worth is a large movable rack in which several cycleplots may be placed one above the other. By aid of the rack, each plot in turn can be brought directly in front of the illuminated ground-glass and analyzed. The plots are arranged so that their dates coincide; hence in a second's time one can change from the inspection of one record to that of another. This makes the comparison of cycle characters in different records very rapid and accurate. For instance, the individual curves of trees in a group can thus be placed one above the other and the group cycles derived by the rapid comparison of the different records. Comparisons are so quickly made that Mr. Schulman has often called the process "simultaneous analysis" because the time interval between the views of successive patterns is almost negligible.[1] The rack was first constructed about 1921 in an attempt to carry dating by cycles through Arizona trees and into California sequoias. In a considerable number of tests we find that results are closely alike, whether by analysis of a group curve or the separate analysis of the individuals composing the group. A comparison between the results of using these two methods is shown in figure 35.

OPERATION AND CHECKING

In performing analyses with the cyclograph, the outward movement of the mirror causes rows of maxima to rotate in a clockwise direction. When any row reaches a horizontal position indicated by a stationary thread in the focal plane the reading is taken (see Plate 15B). It is standard practise to note this reading of cycle length while moving the mirror outward and to repeat the reading on moving it inward. The different approach sometimes causes slight change in estimate of the true setting. Record is kept of both readings and the mean taken.

According to the importance of the case, further checking is made. The cutting line is put on an inverted curve and cycles are accepted as valid that are common to the two tests. It is, of course, most desirable to have someone else try the analysis, but for years until very recently that was impossible. In 1926 the first wholesale analyses were made of the 42 western groups and certain general characters of apparent importance were noted and needed checking. Before publication of Volume II, *Climatic Cycles and Tree Growth,* in which the results had been tentatively placed, resort was made to checking by replotting at unknown scale and making the analyses myself. This was done and results obtained were incorporated as a foot note on page 124. This check at unknown scale is given in *Reports of Conferences on Cycles,* Carnegie Institution of Washington, 1929.

Accuracy and Limitations—During the twenty years of use of the cyclograph, checking has been done as described, but the need of determining fundamental errors, limitations and capacities of the instrument, was fully realized. Formal tests along these lines only recently became possible. Mr. Edmund Schulman several years ago became skilled in the use of this instrument and during 1934 and 1935 was engaged in formal tests of the degree of accuracy found in its use. His description of his work is found in the appendix to which reference is made for details. The enormous amount of analyzing that has been done upon a thousand or more cycleplots for many different purposes offered excellent opportunity for comparisons of results. This meant largely the repetition by him of analyses made originally by the writer, together with many additional tests to bring out the comparisons. He found that we might expect a difference of about one per cent in cycle length as the mirror moved out or in. The "unknown scale" test mentioned above showed differences in result of 1.9 to 2.5 per cent in cycle length; different observers obtained results differing 2.5 to 3.0 per cent. Inversion of curves might produce changed reading by 2.0 to 3.0 per cent. Discrepancies in readings occurred almost altogether in very weak cycles recognized at the time of observation as of small weight. Tests were made on synthetic plots prepared in a manner totally unknown to the observer. The analyses of these were satisfactory. I feel, therefore, that the cycle results obtained with the cyclograph by Mr. Schulman and myself may be accepted with confidence.

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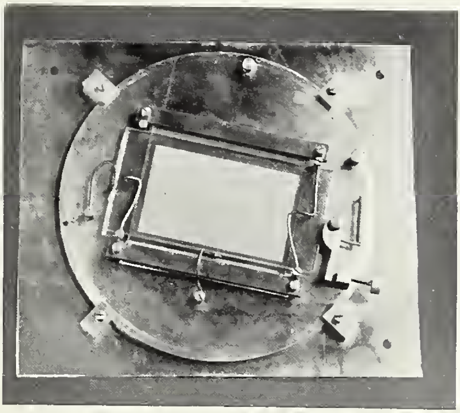
[1] We are also using the word "concurrent" but expect to make the word "simultaneous" literally applicable later on.

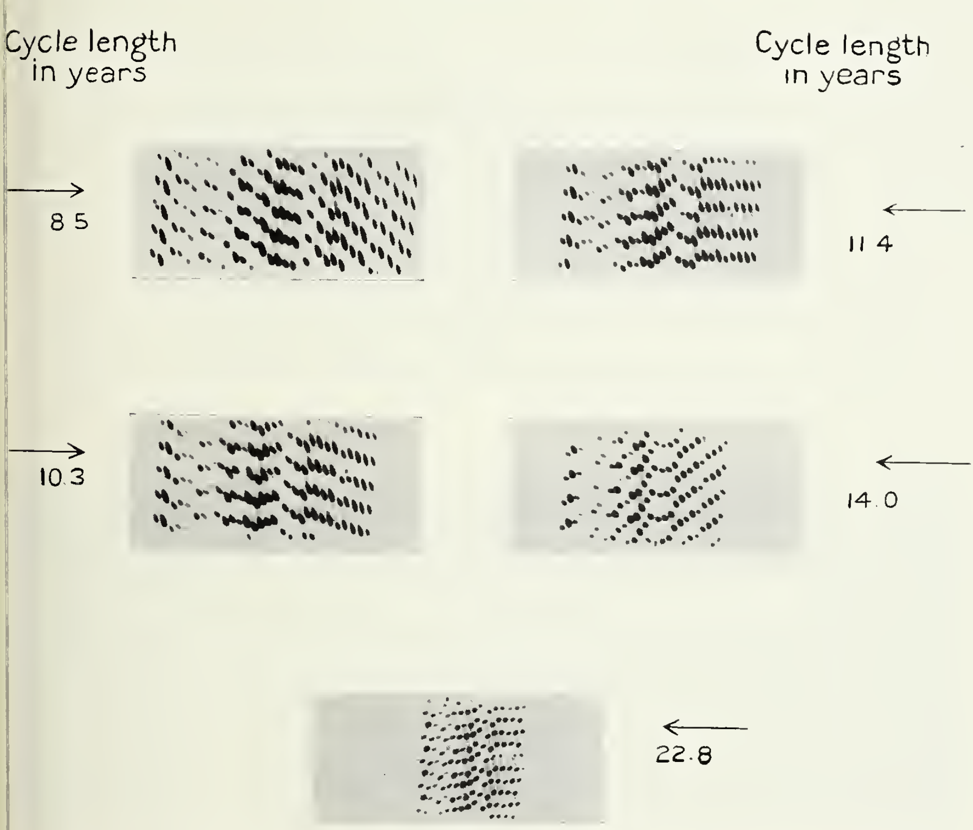
GENERAL CYCLOGRAM INTERPRETATION

The cyclogram as previously described is a rectangular plot with a general time scale usually placed horizontal and progressing from left to right, and a differential time scale in the vertical. The analyzing lines showing in the cyclogram are slightly inclined to the vertical, usually about 17°. It is better to set them a little out of focus so as not to catch the eye, for a cycle is indicated by an alignment of maximal images wholly or partly across the cyclogram and not in the direction of the analyzing lines. A horizontal thread mounted close to the analyzing plate shows in all cyclograms and serves as a reference line for direction of rows of maxima both in calibrating the instrument and for getting correct cycle settings.

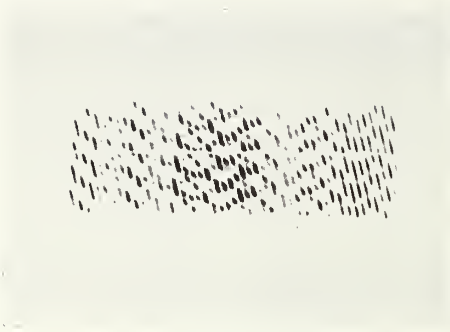
Our cyclograms in published prints have nearly always had the analyzing lines inclined up to the left. The relation of this to cycle length is easily seen by brief study of a cyclogram. A cylindrical pattern of the original data as projected upon fixed analyzing lines has a definite and single time interval across it from left to right whether taken in a horizontal direction or at any inclination. In the horizontal line this time interval is divided by the analyzing lines into a definite number of equal parts, equal to the number of lines that intersect the pattern along the line of the thread. One can count them if desired and divide their number into the time interval and find the cycle represented by the horizontal line. This should check with the cycle setting of the instrument. If the analyzing lines incline up to the left, then a cycle alignment inclining down to the left will take in more of them (than when horizontal) and be subdivided into smaller parts, and thus the cycle length in this row is less than it would be if horizontal. In the same way, an inclination of a cycle row up to the left will cover fewer of the analyzing lines, and so an increased cycle length is indicated.



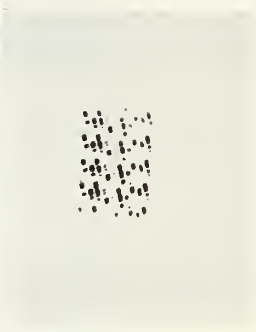
A. Analyzing plate and mounting; the analyzing lines, 50 to the inch and inclined some 17 degrees from the vertical, cover the rectangular area in the center.



B. Cyclograms of sunspot numbers, using centers of mass. Notice change of alignment for different cycle lengths. Horizontal alignments at these settings show the basis for the periodogram of annual sunspot numbers (figure 55). To see cyclograms best hold paper nearly edgewise to the eye so as to look along pattern horizontally.



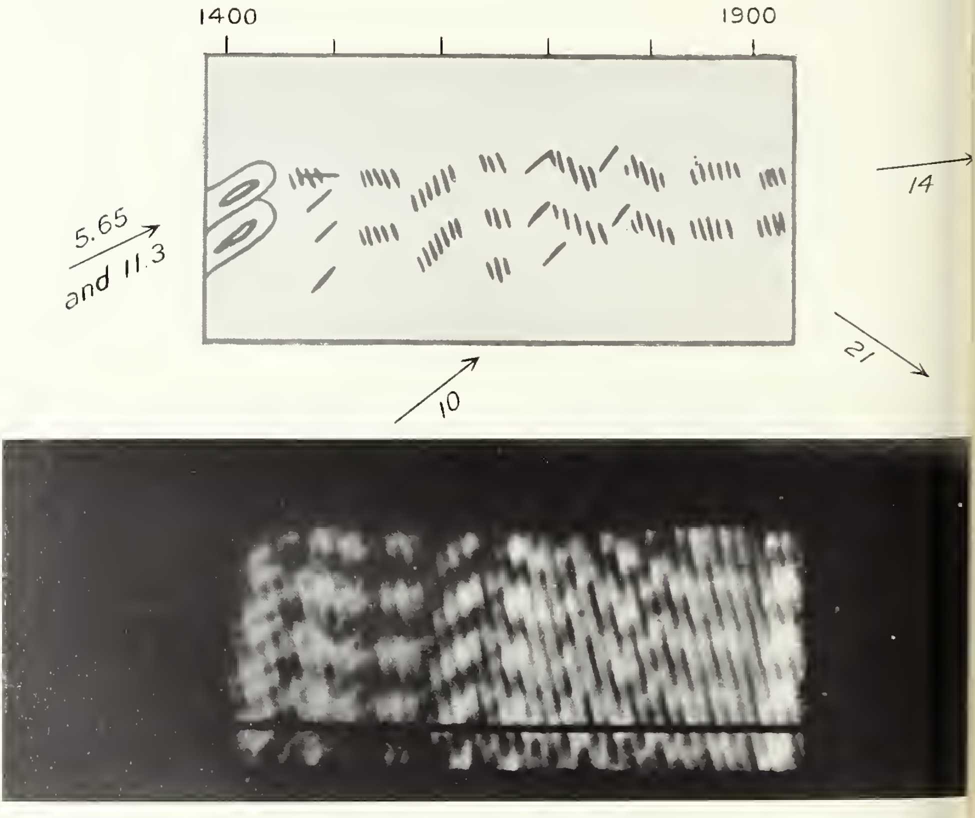
A



B

A. Multiple standard with discontinuous periods at 7.0 (up to the right in right two-third and 9.0 (up to the left in left two-thirds); horizontal direction (thread) set at 8.0.

B. Arizona ring record, FAM, 1700 to 1920 at 21.0 years: shows 23-year cycle dominatin early half (L) and 19-year cycle later half (R). Same data treated differently in figure 16, page 34.



C

C. Analysis of Flagstaff tree ring records (see Chapter II, Cyclogram Reading).

Limits of Range—The track as first introduced in 1918 carried the analyzing box toward or away from the cycleplot placed in a window for sky illumination. In 1920 the reconstructed instrument had for a time a stationary analyzing box and a single movable mirror. This gave a range from 6 out to about 25 units. Two more mirrors introduced into the light path extended the range to about 35 units. For some years now the range has been extended to 42 units by lengthening the track.

One finds from experience that the mirrors must be very firm and not allowed to move in their mountings; the track must be exceedingly straight and without irregularities that might change the alignment of the mirrors; and that the scale along the track should be tested occasionally to make sure that some little vibration has not altered it, or to check for any slight error in adjustment of the automatic focusing device.

Cycle lengths less than the minimum setting of the instrument are rather difficult to determine and are best reached by replotting at enlarged horizontal scale. An attempt was made to use finer analyzing plates with more lines to the inch. But that was found to change the scale readings of the instrument and the pattern looked unfamiliar; so we resorted to replotting. A scale of x4 is used more often than any other. It works well in testing the "2-year" cycle (Chapter V). Of course, plots at odd sizes of scale are sent to us for analysis and corrections are readily applied to the readings. Tests of cycle values at "unknown scale" need only a change of plus or minus 10 to 50 per cent; a pantograph will do this quickly and accurately.

Resolving Power—One might class under the resolving power both the lower limit of the cycles that can be seen with the instrument and the accuracy with which a setting is made on a cycle. The former is a question of range but it is not so much a mechanical limitation as a mathematical or statistical one. It takes 3 or 4 points in the data to locate a cycle. Our smallest reading is 5.0, which seems quite safe. But the Hanned curve is used in 90 per cent of our work and this process enlarges the independent terms and so there are less than 5 in our 5.0 cycle. A running mean of 3 gathers 3 together in one point, reducing the number of original data to one-third, and one could not rely on settings at 5.0. But the Hann has a statistical "conservation"[1] of less than 3; it may be as little as 2, for it does not remove entirely the effect of strong individual departures. At any rate, in a Hanned sequence we readily see cycles at 4 and even sometimes cycles at 3. This is not by direct setting at these figures but by harmonics that are more easily reached.

The accuracy of making a setting on a row or alignment of maxima depends on the length of the sequence of maxima, the precision in periodic occurrence of the maxima, on the number of repetitions of the cycle and on the percentage duration of the maxima in terms of the cycle length. This last is usually a quality in the data, but it also depends on the size of the opening in the analyzing lines expressed in per cent of the width between the centers of the lines. This then becomes in some cases a limiting factor in the accuracy of setting. In early forms of the cyclograph this ratio was

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[1] See page 58.

0.3; then it was reduced to 0.25, and now for some years it has been close to 5 per cent of the constant spacing of the lines. This opening may be said to smooth the data by a running mean of its equivalent percentage of the cycle length. The smallness of the opening reaches a practical limit when the cyclogram becomes too faint to be properly seen or conveniently photographed.

Lag Analysis—This refers to two prisms so arranged close to the main cylindrical lens of the cyclograph that the beam of light from that lens to the analyzing plate divides into three parts, two of them making displacements of the cylindrical pattern on each side of the normal by an amount equal to the space between the analyzing lines. In this way analysis is made of the data in normal position and with lags of one and two cycle lengths all at the same time. This is the equivalent of averaging overlapping cycles, which has been found very efficient.

A small pantograph is being arranged by which to sketch at once any pattern on an enlarged scale. A photographic attachment has long been used for similar purpose but it is less rapid, though more accurate. A number of moving pictures have been taken of the changing cyclogram as the mirror moved outward, each one built of about 650 separate exposures. The attachment for the purpose was built by Dr. V. A. Brown and the pictures were taken in 1929 in our laboratory. The pictures show well on the screen but improved projection devices and other features are needed to make these pictures a practical aid in analysis.[1]

CYCLOGRAM READING

Attention is called to Plate 16C which gives an analysis of 500 years of tree-ring record near Flagstaff. A cyclogram from these data was illustrated in Volume I, Plate 12f, and this cyclogram is taken from Volume II, *ibid.*, plate 9, figure 7 and figure 19, number 7. Our plate includes the explanatory diagram, showing the cycle lengths indicated in the various alignments. The setting is made at cycle length of 14 years. One has a choice here between a slightly varying line that passes horizontally through all the data at an average value of close to 14 and a straighter line at 14.2, with a 180° phase reversal at 1820. There are often some signs of double crests in the 14-year cycle and such a phase reversal is not an impossibility.

From the beginning at about 1400 to about 1635, an 11.3-year cycle (or close to that) is evident if one looks at a low angle across this cyclogram. During the early part, and even to 1520 or so, this 11.3-year cycle shows two crests and thus becomes a Hellmann cycle. The 57-year beats of interference between 11 years and 14 years are conspicuous. From 1650 more or less to perhaps 1800 one can see the sharply inclined lines of a 10-year cycle, or coarser lines slanting the other way that read near a 21-year cycle. This cyclogram was made from an early plot that did not carry quite the technique used today but it approximated closely enough to give a good illustration. (Another cyclogram reading is given on pages 122, 123.)

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[1] Construction of a modified form of cyclograph with a much shortened track, is now in progress.

III. DISCONTINUOUS PERIOD IN CYCLOGRAM ANALYSIS

THE CLIMATIC DILEMMA

Cycles in natural sequences and especially in climate have a very confusing tendency to stop. Heretofore, if a cycle stopped, its consideration was dropped, for on averaging further data its mean amplitude naturally grew less and less and became negligible as more and more terms were included. This was taken as a sign of its non-importance.

A few students have examined these cycles that stop; others say that they do not really stop—they merely interfere with one another and appear to stop. At this moment, that point does not need to be settled. Many interested persons have taken an easy course and become conservative and say that probabilities derived from harmonic analysis settle the matter, and all these temporary cycles are imaginary. The word imaginary in this case is used in its technical sense and amounts merely to a denial of permanent reality. This in turn in the minds of many people has led to the thoughtless denial of any reality.

We can understand why the year and the day and other astronomical cycles, including a family depending on the moon, must last indefinitely, but there are vast numbers of oscillations in nature that do not last: a bell's vibration is dampened; waves on water fade out; a cyclone movement is short-lived, and so is a sunspot. Rotations in fluids may show different rates; the rotation of a tornado varies in velocity and stops eventually.

These cycles in climate are very real, indeed, while they last, but localities differ in their display. Our Atlantic seaboard, for example, seems less affected by slow climatic oscillations than Arizona. People living in semi-arid regions are more likely to become conscious of them. So it came about that after living years in the Southwestern climate the writer felt the intensity of its ebb and flow in units longer than the year, and after finding age-long records in trees, worked up the cyclogram method of analysis in order to learn something about these cycles in trees and climate, that have not been properly examined heretofore because they do not last. This has opened a realm of cyclical facts in climatic phenomena of which some of the most interesting are similarities over large terrestrial areas and even between terrestrial changes and changes in solar activity. And it is in these cycles that the resemblances between sun and earth are found.

PROBABILITIES AND CYCLES

Cycle study by harmonic analysis in the last 30 years has provided a successful display of new and long-lasting astronomical periods, chiefly those depending on the moon's motions. For example, the lunar "tide" in atmospheric pressure[1] and the allied lunar diurnal variations in the terrestrial magnetic forces[2] are among the very satisfying results. But in the analysis of climatic changes and even in solar variations, harmonic study has produced a large number of unconnected facts, each one of which has been regarded with distrust because it did not match the astronomic cycles in persistence of activity. To these unconnected facts the laws of probability have been applied in the hope of getting something tangible, but little or no encouragement has been found.

The idea of discontinuous periods, that is, of cycles localized within a special part of a time sequence, seems to the writer to open a new field in cycle study which has hardly yet received serious consideration. Previous to the opening of this new field the discovery and careful study of climatic cycles was usually a matter of accident. A common way to search for them was to plot a curve of data and test it by eye without mechanical device of any sort. Faint permanent periods not evident in that way were appropriately called "hidden periodicities." If Schuster had merely applied analysis to the sunspot record as a whole he would perhaps not have seen any localizing, in time, of special cycle lengths. However, he did find some evidence of localized cycles by dividing his data from 1750 to 1906 or so into two parts. He thus obtained more detailed values which he displayed in the now famous periodogram.

In 1914, H. H. Turner in extending a similar study worked out the "points of discontinuity" in the sunspot sequence since 1750. One feels that he was rather specially impressed with discontinuity in amplitude as would be natural in harmonic analysis. At almost the same time (late 1914) the writer obtained his first automatic cyclogram (Ap-J, April 1915, pages 173–4) and found the discontinuities in period laid bare for all who understood the cyclogram method. The multiple plot had in 1913 already shown points of discontinuity.

Clayton encountered a temporary period as long ago as 1884–5 in his studies of short cycles in climate (*A Lately Discovered Cycle*, Amer. Met. Jour., vol. I, pp. 130 and 528). Later he formulated the idea of phase reversal and found it frequent in climatic cycles.[3] Arçtowski has investigated short cycles of 1 to 4 years in weather elements. Alter, recognizing the idea of discontinuity, has made extensive and fine use of subdivisions of his data in order to show that each part independently gives the same results. Subdivision aids in localizing cycles and yet it can not be carried far because the fragments of data become too short. Cyclogram analysis carries subdivision to the individual maxima but it gives results only when enough of these maxima unite into a definite pattern.

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[1] S. Chapman, see Bibliography, 1935.

[2] S. Chapman, see Bibliography, 1925. J. A. Fleming, see Bibliography, 1932.

[3] His continental movements of climatic waves are likely to prove of the first importance as are his results on terrestrial temperature reactions to changes in solar radiation. Abbot and Clayton have contributed to similar studies in North America and especially the former has supplied the fundamental data on radiation. Arçtowski has shown the movement of climatic waves.

The sunspot cycle was recently described to me as a succession of changes in phase. Upon first hearing this, it seemed a complete disagreement with our results with cyclogram methods. But on consideration it grew to be a good partial statement from the viewpoint of the harmonic approach. Since harmonic analysis assumes fixed testing periods, any departure in period length comes into view as a change in phase and is so expressed. Hence, it is possible that this statement of phase changes in solar data is an attempt to express the same thing that I call a sequence of discontinuous periods. The critical observational fact in the harmonic method of expressing solar changes is whether the phase changes occur just one at a time or shows a succession of similar changes. The former is a genuine change in phase; the latter, of course, is a genuine change in period, and that, it seems to me, is more closely describing what is taking place in the sequence of annual sunspot numbers. In the cyclogram this difference is highly prominent.

The great advantage of harmonic analysis is that its results may be evaluated by the laws of probability whose principles distinguish between "real" and "unreal" results. These adjectives practically refer to permanence; a cycle is real that lasts through the data and eventually rises above random effects; even a very weak cycle observed in a long series of data may be strengthened by repetition and may give an average easily recognized as real, while random effects are smoothed out by averaging the repetitions.

Students of harmonic analysis had long since observed that cycles in natural phenomena often exhibit a relation between several successive values, statistically called conservation. This has an effect on the cyclical characters in the data and affects the reliability of the results. The cause of the conservation is not involved in its purely statistical study.

BARTELS' DIALS

Two German students of cycles have approached somewhat nearer to the idea of discontinuity, Bartels and Stumpff, the former by development of harmonic analysis methods and the latter with theory and a mechanical process.

Bartels' work appears in *Random Fluctuations, Persistence and Quasi-Persistence in Geophysical and Cosmical Periodicities* (Terrestrial Magnetism and Atmospheric Electricity, vol. 40, No. 1, pp. 3–60, March 1935), and in other papers. In carrying out a skilful study of probabilities as applied to periodicities in magnetic phenomena, he has presented mathematical processes that take conservation into account and has recognized and named certain characters that identify with the phenomena long observed with the cyclogram. These characters are found in his "harmonic dial" and his "summation dial," particularly the latter with its significance and the tests applied to it. Thus I hope cyclogram usage and results will become clear to astronomical and statistical students.

He investigates the 27-day period in 28 years of daily records of the international magnetic character figure C, which is simply the magnetic disturbance on the earth estimated by the various observers on a scale of 0 to 2. This disturbance is attributed with confidence to a solar origin. The 27-day period is an approximate synodic rotation of the sun in the average spot latitude that is found to occur in the late parts of the 11-year sunspot cycle.

The character figures for each 27-day interval are in effect reduced to the nearest sine curve of 27-day length, and the amplitude and phase derived. In the harmonic dial[1] these amplitudes and phases are expressed on polar coordinates, the phase being assigned a certain direction from the pole, and the amplitude being represented by the distance from the same. This is repeated for the 378 rotations and a cloud of dots obtained, as in figure 25. If these dots center on the pole, there is no "real" period. If, however, there is a period present, the center of the cloud of dots will be some distance away and will show the final total amplitude and phase by its direction and distance from the pole. To show reality of a cycle under test, the data are subsequently massed by two's, three's, etc., in larger and larger averages (not

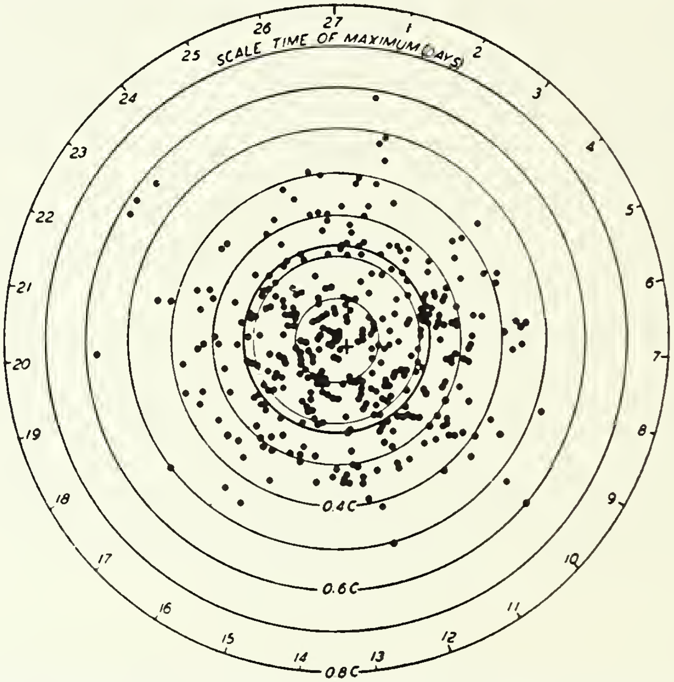

Fig. 25—Bartels' Harmonic Dial of International Magnetic Character Figure C. (From Terrestrial Magnetism and Atmospheric Electricity, March 1935.)

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[1] In the nomenclature proposed in a preceding chapter this would be called a summation or integration dial as it is without a time scale, and figure 26 would be an extended dial.

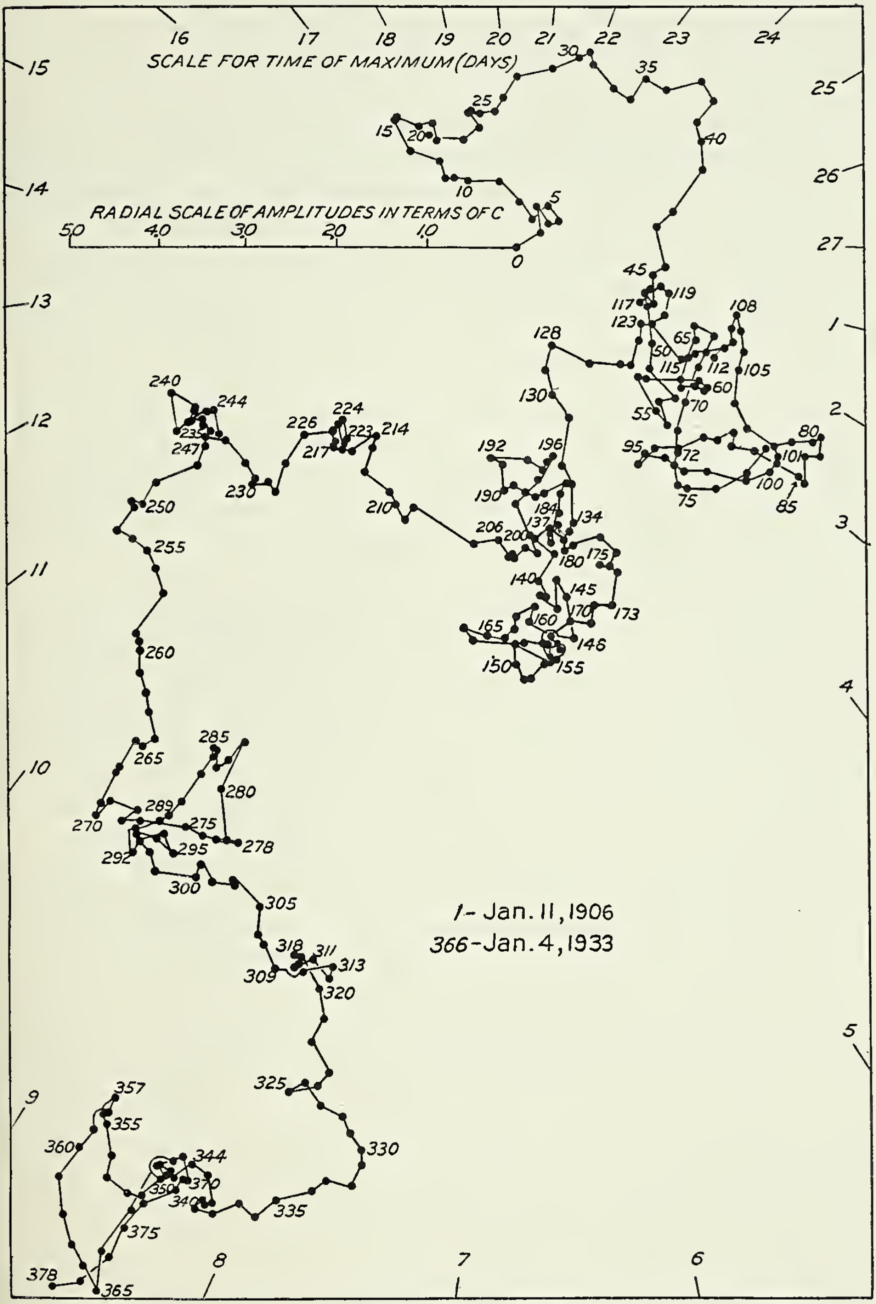

FIG. 26—Bartels' Summation Dial. (From Terrestrial Magnetism and Atmospheric Electricity, March 1935.)

overlapping), thus reducing the number of dots and bringing them nearer their center. If by this means the location of the cloud is found to remain distant from the pole, the reality of the period becomes more and more evident.

The summation dial, figure 26, is of special interest to us, for it represents the same phases and amplitudes stretched out into a time sequence, though an irregular one. It is, therefore, an extended curve, for it gives facts at successive equal intervals of time through the full data. Figure 26 doubtless was his basis for introducing the middle term in his series of three classes of effects: random, quasi-persistent, and persistent. The diagram at first glance could be divided into "tangles," or random motions, and "arcs," which have a directional effect; in these last the quasi-persistences are more easily found.

Since the harmonic method uses a constant period of 27 days, any actual change in it becomes expressed as a change in phase; and since phase is represented as a position angle (direction from pole or a line parallel to such direction), a slight semi-persistent departure in period from the assumed value is expressed by a series of amplitudes pointing progressively in a changing direction; this produces an arc.

To look at this diagram and think of its possible solar meaning is perhaps perfectly natural. As the period here used is the time of rotation of the sun, the tangles which occur at sunspot maxima and minima mean that at such times magnetic forces are reaching us from widely distributed solar longitudes. This is to be expected at maxima. Dr. Bartels has observed its occurrence also at the beginning of each new sunspot cycle, which explains its presence at minima. The "arcs" indicate a tendency for magnetic forces to emanate for considerable intervals from some localized longitudes of the sun.

Quasi-Persistence in the Summation Dial—The important feature in Bartels' summation dial, figure 26, is the representation on an extended time scale of certain changes in cyclical character and their evidence of temporary stability, if we can so term it, which he calls quasi-persistence and which I shall indicate in these paragraphs by the initials QP. Amplitude QP's in the summation dial are indicated by the number of equal lengths in succession in the short, straight lines, without regard to direction, such as shown in figure 27a. A quasi-persistence in period is indicated by successive, equal angles between these short, straight lines. This develops as a curve and may not have any QP in amplitude, as in figure 27b. A complete reversal of phase by 180° has often been suspected in climatic cycles. Such a change in a summation dial would make a pattern somewhat like that in figure 27c. It is possible that a change in phase occurs by some other fraction than $\frac{1}{2}$.

Quasi-Persistence in the Cyclogram—The cyclogram is an automatic plot in three dimensions capable of instant adjustment over a wide range of cycle lengths. In this analysis the portion of the curve below a "cutting line" along the lower minima is commonly omitted during analysis, which is analogous to the usage of harmonic analysis in taking values from a mean and not from a base. In the cyclogram process we still keep the base available for the measurement of real amplitudes by a photometric method.

A discontinuous period, or QP, is recognized by the maximal images forming in an obviously straight line, which means constant cycle length. The features that attract attention in looking for QP's are: number of repetitions of the cycle, straightness of the line of maxima, which is the same as phase stability, and strong amplitude due to freedom from interfering maxima.

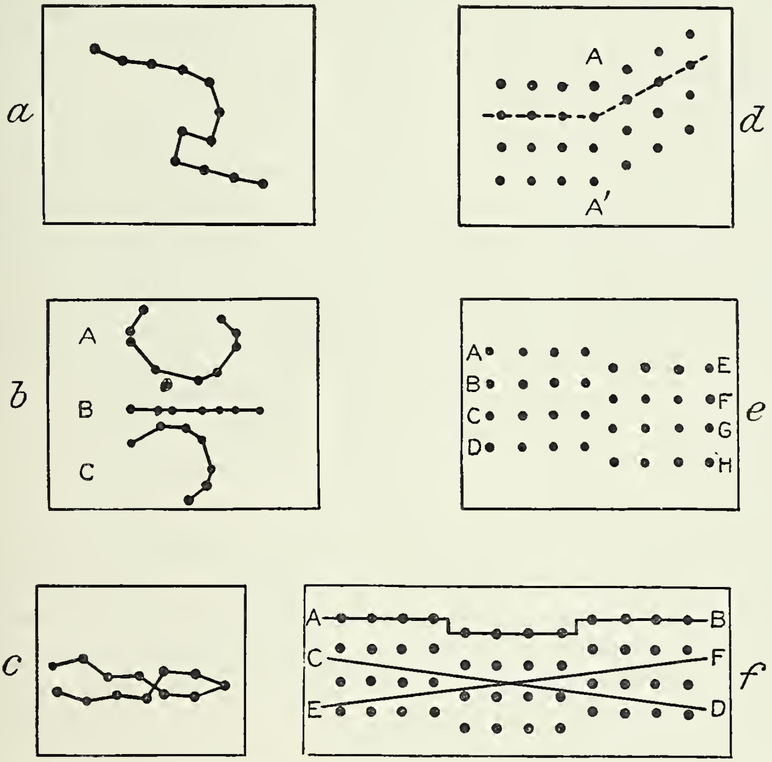

Fig. 27—Comparisons between Bartels' dials a, b, c and cyclogram analysis d, e, f; a, quasi-persistence in amplitude, b, quasi-persistence in phase, and c, phase reversal; d, change of period (same as continued phase change), e, phase reversal, and f, periodic phase reversal. In the dial, time progresses along the bent lines; in the cyclogram, it moves horizontally left to right.

The cyclogram is built fundamentally on cycle length and so differentiates at once between quasi-persistence in period and in phase. This is illustrated in figure 27d, which shows a change in period at A A′ by a change in direction of the horizontal alignment of dots. A complete 180° reversal in phase is shown in figure 27e. The horizontal rows a, b, c, and d are repetitions of the same sequence of maxima. A 180° phase reversal puts the new maximal lines, e, f, g, and h in the same direction as before but at vertical position half-way between the a, b, c, and d lines.

A difficult case, sometimes occurring in natural data, is well brought out by this method. When the 180°-phase reversals occur at regular intervals, as in figure 27f, the pattern obviously contains an interference between two periods, of which one takes the definite direction AB and the other may be either CD or EF with "infection," as Bartels has called it, from AB. A pattern of this type was encountered in a Southern California rainfall cycle near 2 years in length, that could only express itself in winter and thus clings a bit to the annual value. In the cyclogram obtained, the interfering cycle could be read at once as 1.8 years or 2.2 years and the 1–2-year cycle could be stated as a 2-year cycle with regular phase reversals or a 1-year cycle with alternating intervals of appearance and suppression.

Evaluation of Quasi-Persistence—Bartels has done more than recognize QP's; he has arranged a criterion[1] which may be applied to express their weight. This is derived through a principle of probability. In setting up a correct average under normal distribution, the probable error of the average is inversely proportional to the square root of the number of terms; the standard deviation is the square root of the mean square of the residuals. This may be applied to separate random values which are to be averaged into a mean but it may be applied equally to separate random sets of values such as a cycle length, commonly used in the summation process in deriving the form of a cycle that exists in a series of data. A "set" is a row of data covering one period of the period length considered. Bartels compares the standard deviation of the mean of the sets with a theoretical value derived from the average standard deviation of a single set, and uses the $\frac{1}{\sqrt{N}}$ relation stated above for estimating the random part of the final values. Thus, if we have N random sets of values in which the first set shows a standard deviation of m_1 and the second of m_2, etc., the average standard deviation m of the sets is the square root of the fraction $\Sigma m_n^2/N$. The mean of the N random sets of values theoretically would have an average standard deviation of $m/\sqrt{N}$. If, therefore, we divide the actual standard deviation of the mean by this theoretical value for random data, we get unity as a ratio in case the data are really random values and a sufficiently large number are used; if, however, the values are not random but tend to show the same cycle in each set, the standard deviation of the mean is larger than this quantity for random values and on being divided by it gives a ratio over unity, which for the moment we are calling the Bartels A.D. ratio or the A.D. ratio. Such a ratio, therefore, becomes a measure of the reality of a cycle when compared with unity on one side and with $\sqrt{N}$ on the other. This latter is the maximum value it can reach in the case of a cycle with no random values.

The Conservation Factor[2]—Conservation in natural sequences was recognized by the writer very early in the study of tree-ring records because it is prominent in them. It was not at first called by that name but simply described as a lack of those short cycles which are so characteristic of scrambled or random data. It was used in 1922 and especially in 1932 to distinguish between random and natural sequences. It had even started the idea of a natural cyclic unit in climatic change which might include several terrestrial units such as the year. Each climatic cycle (even though temporary) could possibly be called a natural unit of which several could exist at the same time. In 1932 Dr. Alter had applied his lag correlations to certain tree-ring data and reported strong conservation of 1 to 3 years. When I proposed a natural unit of this sort to Dr. Bartels he referred to his σ, described below, as his idea of a natural unit.[1] This σ would become a test of the presence of conservation and a measure of its effect on the data.

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[1] C. F. Marvin published in 1921 his "periodocrite" test to which Bartels' criterion bears a relation.

[2] In statistical studies conservation refers to correlations between successive values without regard to the physical cause.

From the viewpoint of probabilities (and following Dr. Bartels' discussion) this conservation is the tying together of several successive values so that they are not independent. It affects the reliability of periods suspected in the data, which should be evaluated on the basis of the number of independent terms. So we desire to find how many of our original terms must be united into one term in order to make the values independent of each other.

Bartels calls the conservation factor σ and describes it (and therefore the natural unit) as the equivalent length of the quasi-persistence. The Bartels ratio, which we will call B, may be stated thus:

$$\frac{\mathrm{M}}{\dfrac{\mathrm{m}}{\sqrt{\mathrm{N}}}} = \mathrm{B}$$

in which M is the standard deviation of the mean; m is the average standard deviation of the sets as before; N is the number of sets and B is usually more than unity. In random data B is unity. Therefore to make our formula produce unity on the right-hand side of the equation—as in random data—we must divide each side of the equation by B and we get (placing B under the radical):

$$\frac{\mathrm{M}}{\dfrac{\mathrm{m}}{\sqrt{\dfrac{\mathrm{N}}{\mathrm{B}^2}}}} = 1$$

This B^2 is Bartels' σ or the number of sets or unit values, whole or fractional, that must be grouped together in order to get independent terms, for it divides the number of sets N by a quantity over unity and reduces the number of independent sets. Of course, we understand that all this becomes more strictly true as the number of data or sets increases very greatly.

For example, in an apparent 11-year cycle in Eberswalde trees (giving a correlation coefficient of 0.51 ± 0.07 with the smoothed annual means of the sunspot numbers) we find 7 sets with an average standard deviation of

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[1] See more recent paper in Bibliography, Bartels, 1935.[2]

0.206 per set and a standard deviation of the mean of 0.124. So the Bartels ratio for this sequence is 1.6, which places it in the realm of reality; the maximum possible value is $\sqrt{7}$ or 2.65. His σ becomes $(1.6)^2$ or 2.6.

It has been suggested that we use the fraction of 1.6/2.7 or 0.59 as the reliability index. But that seems undesirable because we are only using two of the necessary three terms; the unity term has disappeared, and we can not let it disappear because it varies with every different number of sets. In the present case the unity in the same proportion would be 0.37. We might take the logarithms of the three terms; they are 0, 0.20, and 0.43. This gives us 0.47 as the index. For the present we should perhaps tell the story by saying that in 7 repetitions of the cycle the QP factor is 2.6, which is 0.37 of the continuous length 7.

At this time the subject should not be carried further, but we note that if and when the variations that we here class as random become assignable terms in other cycles, the variations lose a portion of their random character and the QP factor will more nearly reach N, the number of sets used.[1]

This process of Bartels' seems a very promising method of evaluating a cycle. In his application of this process to the magnetic character figure C, he uses the full series of data in his 378 sets of the cycle length, which implies that the QP is not localized at the few places where it has been recognized but lasts throughout the data as a general solar character. While we, on the other hand, are trying to localize such characters and learn more about them, we appreciate the high value of his result as it stands; it is analogous to a first statement of mean annual rainfall of a new locality as compared to the more detailed monthly values to come later.

Bartels' Multiple Plot of the Magnetic Character Figure C—The writer feels that Dr. Bartels had previously reached important results in a graphic analysis of discontinuous periods in the magnetic character figure C contained in his paper of 1932, *Terrestrial-Magnetic Activity and its Relation to Solar Phenomena* (Terrestrial Magnetism and Atmospheric Electricity, vol. 37, No. 1, pp. 1–52, March 1932). To use a term already employed by us, his long chart of symbols showing the daily values is a multiple plot.[2] Like our figure 14b, page 31, it corresponds in function to a summation table and represents quantities by symbols that catch the eye. It thus has the qualities of the plot mentioned and by the eye alone periods and discontinuities may be read off from it as from a cyclogram. Without really naming it as a form of analysis, Dr. Bartels has correctly used it as such. He derived very important inferences from the diagram. He confirmed the persistence in solar longitudes of magnetic source areas which he called M-areas, finding them largely independent of sunspot activity. He quotes outstanding examples of long 27-day recurrences of disturbed days: 1910–11, 13 rotations; 1921–22, 14 rotations; 1929–31, 17 rotations. He makes some references to activity at opposite longitudes on the sun (as if there were a 13.5-day period)

[1] The co-existence of other cycles may seriously affect the A.D. ratio.

[2] Chree and Stagg used a multiple plot in 1927; see Bibliography.

and to indications of longer rotation periods (synodic) than 27 days. These features of solar records are examined below by the cyclogram process.

Significance of Conservation—A better understanding will be reached of the analytical work of Bartels and others if we give some attention to the physical meaning of conservation in certain solar problems. We can readily see that daily values of sunspot data have a large conservation factor both statistically and physically; for nearly all spots or groups would be visible continuously for 10 or 12 days. Daily results then would amount to a running mean of 10 or 12. The monthly number, therefore, is a good figure for general use. However, daily observations on spots within definite longitude zones some 10° in width would be very desirable in order to secure closer correlation in time with magnetic data. This need could be worked out in the frequent photographs of the sun taken at many observatories.

The magnetic character figure is believed to be more nearly related to the solar activity near the sun's meridian, and therefore it perhaps involves an equivalent running mean of only 1 to 4 days. Hence, in our accompanying analyses of this solar record we can use 3-day means and get probably all the "resolving power" which the data can yield.

Bartels' estimates of quasi-persistence in the paper of 1935 were made upon a similarity from rotation to rotation of the sun and temporary persistence of the source areas of magnetic force in solar longitudes. His value of σ is 3.0 rotations, which means that the quasi-persistent localizing of magnetic source areas averages 3.0 rotations or between 80 and 90 days.

But it is easy to see that at times such as sunspot maxima we may be averaging together outbursts of magnetic activity from many disconnected localities in solar longitude, each of which complicates the problem of real persistence in longitude. Spot groups, and probably magnetic source areas also, cover at maximum a considerable range in solar latitude, and so may exhibit a range in rotation periods because of the important fact that different solar latitudes have different times of rotation. Hence, we have recourse to the cyclogram process which helps to unscramble the various cycles near any desired setting of the instrument. On the first attempt, covering data near the 1923 sunspot minimum, we found so much more evidence of stability in longitude than expected that we seemed to be dealing almost with a new group of phenomena. Cyclograms of the magnetic character figure C are given herewith in Plate 19B. As the necessary discussion is somewhat extended, further description will be found in the next chapter. We find in the above discussion an illustration of how a search into the significance of statistical conservation led to a better understanding of solar problems.

STUMPFF'S PERIODOGRAPH

Dr. Karl Stumpff's researches are presented in *Analyse periodischer Vorgänge* (Berlin, Gebruder Borntraeger, 1927; the method was first described in Astronomische Nachrichten, BD. 223, Nr. 12, 1924). In this book there will be found theory and description of the periodogram and various mechanical methods of producing it. His own method interests us not merely because it produces an analyzing pattern or periodogram that measures continuous periods with precision but also because his "fine structure" displays some basic elements of the cyclogram.

Our automatic cyclogram discussed in the previous chapter is a pattern using space distribution of the cycles in a common rectangular plot, derived all at once from the extended data; Stumpff arrives at a pattern of somewhat similar qualities by a timing device, that is, his pattern is not produced all at once but is constructed photographically point by point. Stumpff's inspiration (like the author's) was Schuster's periodogram and a desire to produce it automatically. We each developed a pattern of cyclogram type and used it in producing the periodogram. The writer began using cyclogram results from the start (1913–14) and essentially abandoned the periodogram after producing actual photographs in 1918.

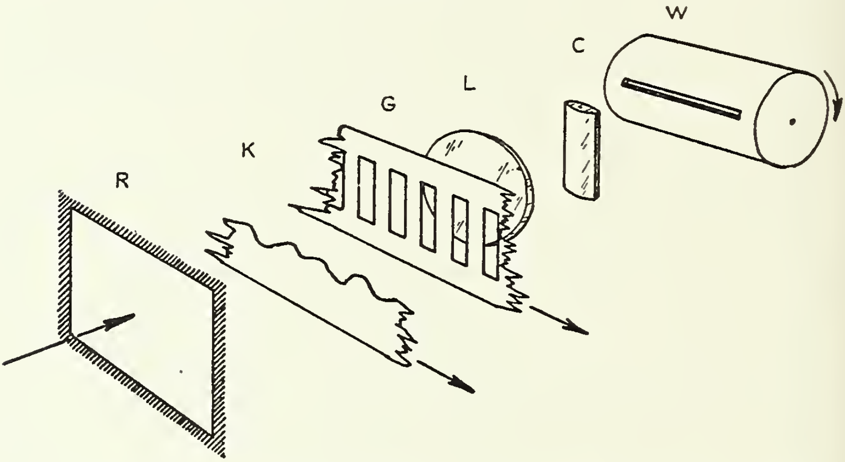


Fig. 28—Plan of Stumpff's periodograph. After Stumpff, slightly modified.

The fundamentals of Stumpff's apparatus are shown in a slightly modified copy of his drawing in figure 28. As I have sketched it here, R is an opening through which passes a bundle of parallel rays that are converged on the cylindrical lens C by a condensing lens L. K is the curve cut out of opaque paper, and G is a grating made up of equidistant openings; each one in width is 50 per cent of the constant distance between their centers. W is a cylinder with a longitudinal slit; within the cylinder a drum carrying a photographic film slowly rotates. Removing K for the moment and holding G stationary, each opening in G will cast an illuminated image upon W, the image being elongated perpendicular to the slit. If we should set G in motion in the direction of the arrow, these images (for which the name "sweep" was long ago suggested) will move to the left along the slit. Now holding G stationary and replacing K and starting the rotation in W, the several openings in G will trace longitudinal lines on the rotating film, lines that are perpendicular to the slit; but these lines will differ one from another in density on account of the variations in the curve K that obstruct one or another opening in G. Now if we start the curve K in motion, the longitudinal lines on the film W will remain straight but will change in density according to the variations in the curve K as each part of it passes across each opening in G; and eventually each longitudinal line will make a reproduction of the complete original data with ordinates represented by photographic density. The result is a "multiple plot" with complete reproductions of the data in equidistant parallel lines. It is easily seen that if the film W moves very slowly in relation to the speed of the curve K, the horizontal offset between these reproductions will be very small; but as the film goes faster the horizontal offset between the reproductions on the film W will be greater. Thus, the offset in the resulting multiple plot depends on the relative rates of motion of K and W.

In our original attempts at analysis there was no fundamental difference between multiple plot and our present cyclogram, merely differences of convenience in production and use. Discontinuous periods were seen in either one. There was a little difference in the formula for getting the cycle length. The multiple plot could be described as a cyclogram in which the two plotting axes are not perpendicular to each other. To get them perpendicular we choose an axis of x, in time, not perpendicular to the multiple lines of the data (the analyzing lines) but perpendicular to the "sweep" lines. It is noticeable that in the cyclogram as commonly reproduced the analyzing lines slant to right or left of the perpendicular (referring to publications subsequent to 1920). Changing the slant from right to left, or the reverse, inverts the resulting plot (fig. 20). The same effects are readily produced in Stumpff's apparatus by giving his grating a slow constant motion; the direction of this motion corresponds to the direction of slant of our analyzing lines and the rate of motion corresponds to the angular amount of slant.

An important difference between the two analyzing methods is that while each can produce a photograph, ours also gives instantaneous visible results and is very readily and rapidly applied to a large range of cycle length. If we understand Dr. Stumpff's instrument correctly it is not so well adapted as ours to the study of discontinuous periods.

In describing Dr. Stumpff's instrument in the last few paragraphs, I have exemplified the production of a form of multiple plot and a cyclogram by his process. Dr. Stumpff's operation of the instrument produces a periodogram. This is done by imparting an accelerated motion to the grating G. When this motion comes into a definite speed ratio to the motion of different cycle maxima in the curve K, a critical resonance point is passed which goes on record on the film in the form of a parabola vertex which can be nicely located, thus giving data for an accurate determination of the cycle length.

APPLICATIONS OF THE DISCONTINUOUS PERIOD

There seem to be several fields in which the discontinuous period should find special usefulness. The first is the determination of the terrestrial areas (meteorological districts) in which similarity in climatic cycles may be found.

This application of our analytical method makes use of tree-ring and meteorological records. The second application will be in examination of the relation between climatic or other terrestrial changes and changes in the sun. A third, equally important application, is the recurrence of discontinuous periods during long time intervals of the earth's history. This makes use of very long records in tree rings and varves.

The fourth and perhaps most general application of the discontinuous period is its quantity production from wide but homogeneous sources and its grouping into frequency periodograms. Such periodograms can equally well be secured from dated or undated material provided the counting is accurate and therefore they can bring together evidence from modern trees, fossil trees, varves, and other sediments. It offers an exceedingly wide opportunity for stating certain general facts about climatic variations.

The fifth and last application of the discontinuous period in this brief list is in climatic prediction problems. Whether climatic cycles are permanent or not, whether they come from the sun or not, they become applicable to climatic forecasting in their function as natural units of greater length than the year. On the basis of the difference between the year and these longer natural units we can improve our probabilities of successful prediction and lessen our errors without settling beforehand the complete physical source of these variations. The fact that now and then one of a group changes or even disappears does not overcome the value of using the cycle complex that is actually in operation. As we find more and more their physical source and the rules of their behavior, the value of prediction will increase toward the desired accuracy. If these longer natural units admittedly emanate from the sun, then observations of the sun containing valuable advance information will become of great importance.

IV. ANALYSIS OF SOLAR RECORDS

A vast amount of solar heat passes out from the sun into space and we ourselves exist by favor of that minutest fraction caught, in passing, by the earth and employed in producing winds and rain and a thousand complex processes, including vegetal growth and even human life itself.

Nothing could be more natural in a discussion of climate and tree-ring growth than a study of the variable activity of this great source of terrestrial energy. Many of the basic facts about the sun were laid down in past centuries; its distance, size, mass, temperature, radiation, and its spots and their periodicity and latitude change. Since 1900 the attention of investigators has gone largely to atomic and spectroscopic studies, the constitution of matter, source of the sun's energy, internal motions of sunspots, and composition of different parts of the sun. More closely associated with our present subject are the improved measures upon the rotation of the sun with its equatorial acceleration (Adams), the persistence of spots in longitude (Nicholson and others), and, perhaps more fundamental, the magnetic polarity of spots and their change at minima, and the polarity of the sun itself (by Hale, carried on by Nicholson).

The sun rotates on its axis in 25 to perhaps 32 days, as seen from the stars (siderial rotation), or 27 to 35 days as seen from the earth (synodic rotation). The equator takes the faster rate; and high latitudes, north and south, the slower. The causes of this "equatorial acceleration" are not yet fully understood although this phenomenon has been connected by some with the planetesimal hypothesis. In order of time, a cycle of spots, from minimum to maximum and back, taking about 11 years, begins at 25° north and south latitude and works to within about 5° of the equator. Rarely one goes beyond the equator. The maximum number of spots occurs at some intermediate latitude. The best visualizing of that change is obtained from a photograph arranged by Dr. W. S. Adams and Dr. S. B. Nicholson of the Mount Wilson Solar Observatory of the Carnegie Institution of Washington, reproduced here by permission, Plate 17. The spots are relatively inconspicuous in small scale photographs of the sun and they have substituted photographs of the calcium clouds or flocculi that surround the spots and are very conspicuous. After allowing for change in slant of the solar equator, one can recognize in them the beginning of the spot cycle at high latitudes, the increase in numbers at somewhat lower latitudes, then the disappearance on close approach to the equator. When this is plotted, it forms what Maunder called the "butterfly" diagram, as in figure 29. Dr. George E. Hale at the Mount Wilson Observatory in 1908 found magnetic effects in the spots involving systematic distribution of north and south magnetic poles in pairs of spots. This polarity was observed to change from "north" direction to "south" direction (or *vice versa*) at the sunspot minima, 1913, 1923, and 1933–34, thus raising many complex questions in the problem and locating fundamental activity within the body of the sun. Thus we see that in studying cycles in the sunspot numbers, the month is the logical time unit, since in that time the entire circumference of the sun is reviewed.

For certain terrestrial effects, however, we need the daily reports. Magnetic storms and the related auroral displays often show direct relation to large spots near the center of the solar disk; the terrestrial effect is observed to follow a day or so late. In consequence of this prompt response, the solar influence in terrestrial magnetism has long been recognized. It is thought to be due to streams of particles coming to the earth at high velocity from the solar surface in or near the spot. Physical connection of these magnetic effects with meteorological conditions and tree-ring growth has not yet been established. It is thought possible that these streams perform some change in our upper atmosphere that influences the transmission of heat.

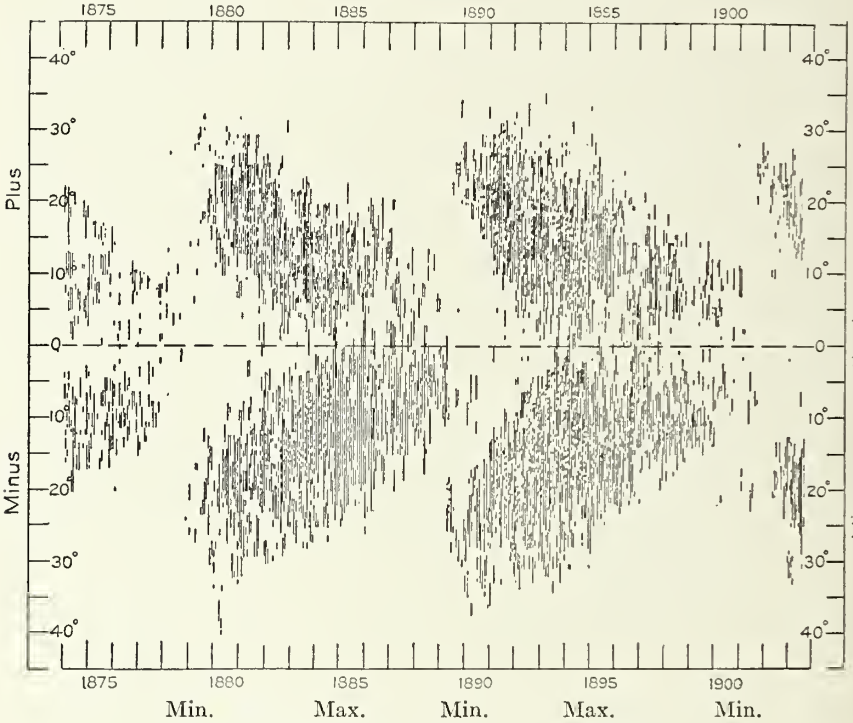


FIG. 29—Butterfly diagram (after Maunder).

Meteorological changes depend primarily on the motion of our atmosphere which results from heat that comes to us with the velocity of light from the sun's surface. Here again there may be effects in our upper atmosphere that

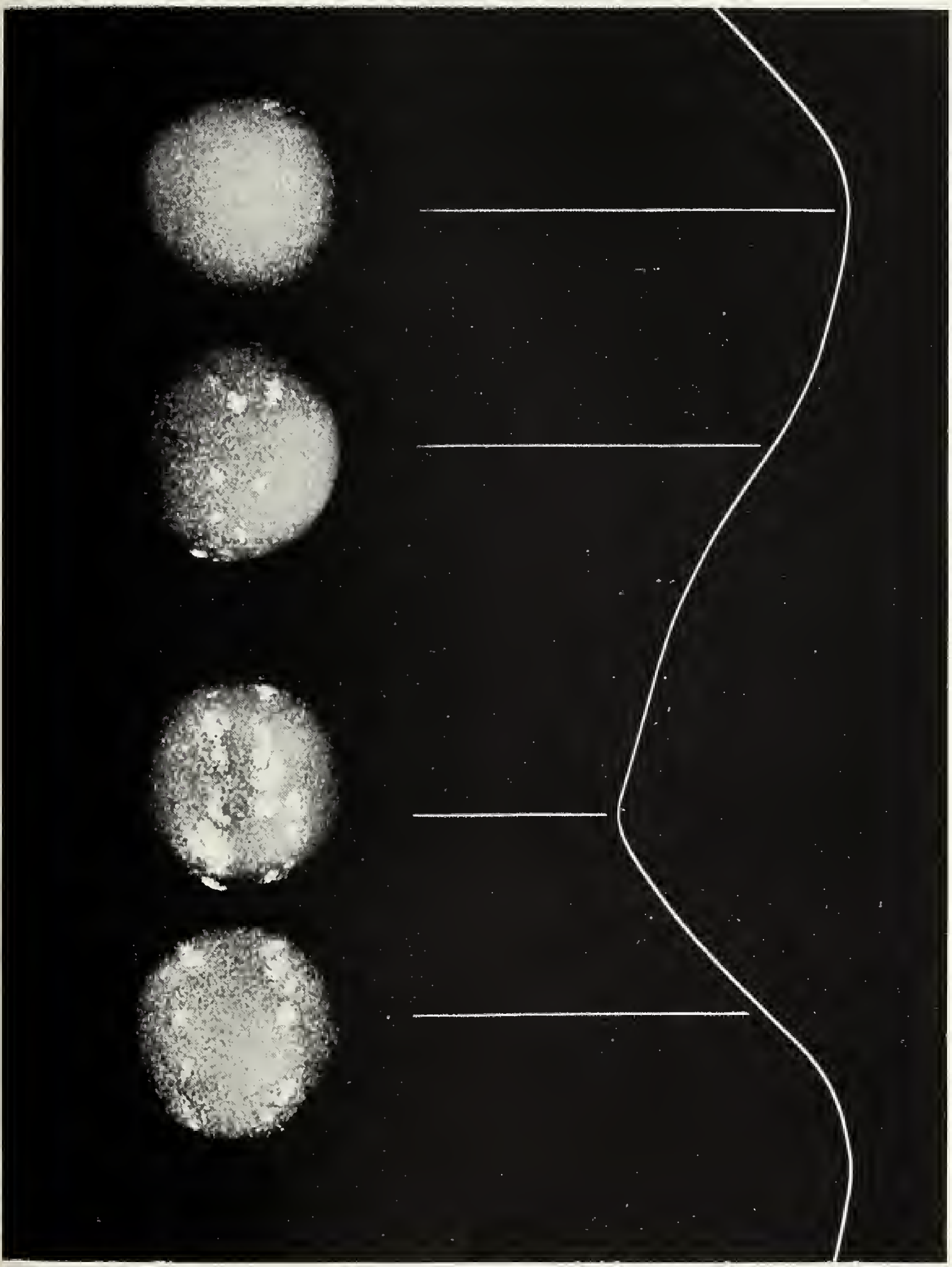
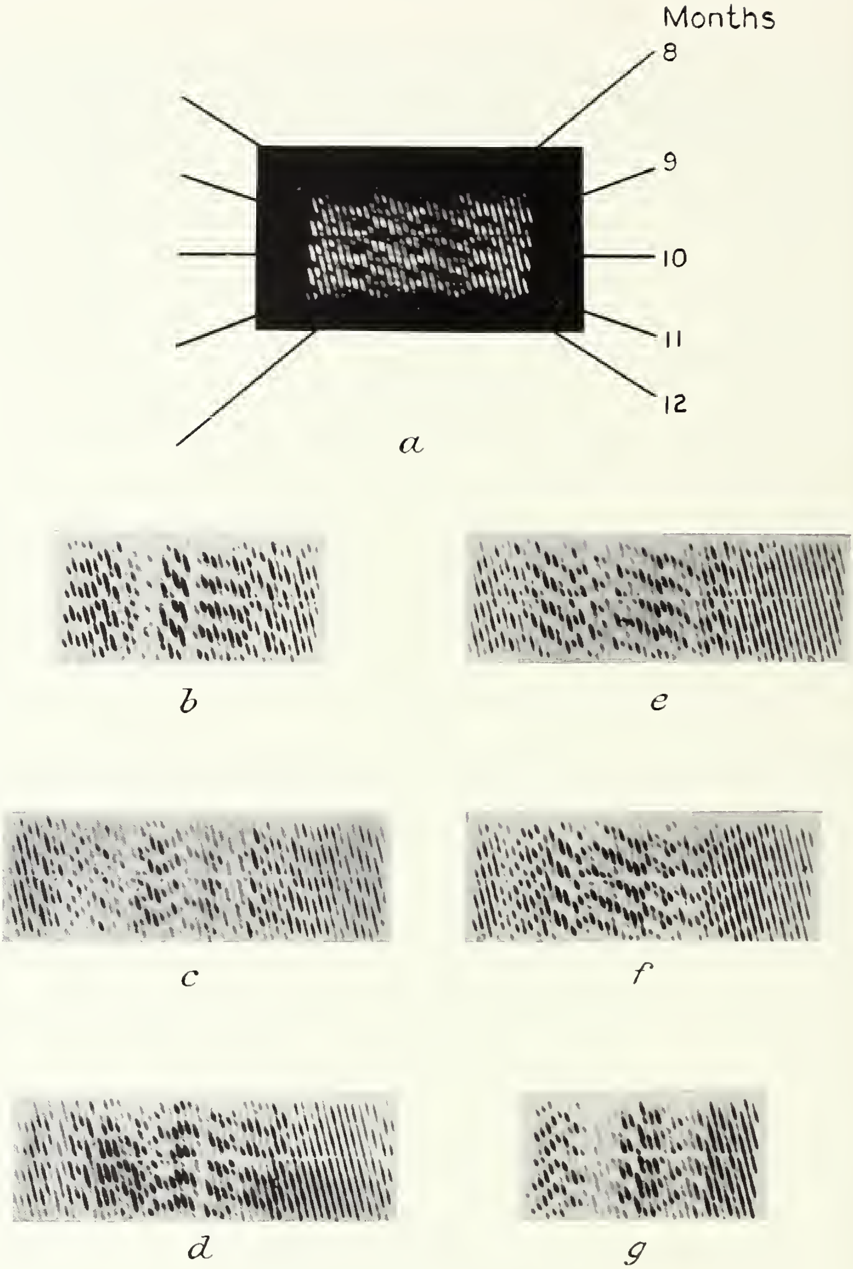


Illustration of sunspot cycle by changes in calcium flocculi; after Adams and Nicholson.



Cyclograms of monthly sunspot numbers, 1750 to 1931: horizontal alignment is at 10 months; 8, 9, 10, 11 and 12-months directions are indicated in pattern *a*; time moves left to right; first and last dates in the patterns are as follows:

b. 1750.1–1779.9
c. 1770.1–1814.9
d. 1805.1–1849.8
e. 1840.3–1884.6
f. 1875.4–1915.3
g. 1905.1–1931.2

influence admission of heat to the lower atmosphere and the earth's surface, but we recognize that the heat radiation from the sun is the obvious factor to be studied in connection with rainfall and tree growth. Thanks to Dr. Abbot and the Smithsonian Astrophysical Observatory, and others, almost daily records of radiation have been obtained since 1918 and we have some values going back several years earlier. These, with the results of Dr. Pettit and Dr. Nicholson of Mount Wilson Solar Observatory, will be discussed later, together with a cyclogram analysis of the international magnetic character figure C. Various long-continued solar records have emerged from these investigations and offer a favorable field for cycle analysis by our method.

ANALYSIS OF SUNSPOT NUMBERS

Very large spots were occasionally seen by the naked eye before the invention of the telescope in 1610, and after that these solar phenomena were observed more or less continuously. After 1750 and especially since 1830, they were watched with care.[1] A study of the periodicities in such records by aid of cyclogram analysis is a most illuminating example of the method and at the same time it is the best introduction to our problems in climatic and tree-ring cycles. There are two parts to such analysis: one treats the well-known annual values commonly called sunspot numbers, and the other handles the monthly values, which are much more irregular. The first series gives a persistent cycle averaging something over 11 years since 1750. The other gives a flow of several cycles, interlacing, mixed, starting and stopping, such as we find in climatic and ring records. We find traces of this second type of cycle in the first series of common annual sunspot numbers. We consider below each of these groups of data in turn and add to them an examination of Abbot's and Pettit's radiation measures and the records since 1906 of the international magnetic character figure C, followed by a review of naked-eye sunspots and northern lights which give traces of solar history centuries before the invention of the telescope.

Analysis of Smoothed Annual Sunspot Numbers—Schwabe in 1843 found that the number of spots on the sun had an ebb and flow, in an interval of 10 or 11 years. They had been well observed since 1750. Starting with that date as a maximum, other maxima had fallen approximately at 1761, 1770, 1778, 1788, 1804, 1816, 1830, and 1837. These intervals are roughly 11, 9, 8, 10, 16, 12, 14, and 7. Here was a scattering of values that started the idea of a cycle as a persistent series of random values that never depart very far from a mean. But later this instability of interval quieted down; since 1837 the maxima have come steadily on a period averaging 11.4 years, 1837, 1848, 1860, 1871, 1884, 1895, 1906, 1917, 1928: many of these dates can not be assigned with exactness but they give roughly the intervals 11, 12, 11, 13, 11, 11, 11, and 11 years.

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[1] The reader is referred to any good recent text-book on astronomy for discussion of modern opinion about sunspots and their cycle. Our sunspot data come from the Mitteilungen of Wolf, Wolfer and Brunner. The pre-telescope data come from Fritz (Reed's translation in Monthly Weather Review) and Maunder in *Splendour of the Heavens.*

In 1906 Schuster performed his celebrated analysis and found several different cycles or periods as shown in his periodogram, our figure 21, page 42. He divided the interval from 1750 to 1906 into two parts and thus secured an improved idea of the variations in the cycle and the localizing of special cycle lengths. Turner in 1913 using similar analysis expressed the "discontinuities" in the cycle, as he called them. A discontinuity is an interruption or abrupt change in length, phase, or amplitude in any cycle sequence. Schuster and Turner, while noticing changes in length, have been strongly influenced by the changes in amplitude, and Clayton by changes in phase. In a cyclogram, however, the story of change in period is laid out clearly for all who can read it. The fundamental form of the cyclogram of the sunspot numbers since 1750 is shown in figure 20, page 39, which gives successive cycle values at about 9.5 years, 14 years, 7 years, and 11.4 years in length.[1] These changes were evident in the first cyclogram photographed in December 1914 (I; Plate 9), and called differential pattern in the Astrophysical Journal, April 1915. We can describe the solar changes as a persistent cycle clinging near a general average of 11.3 years, whose variations between 7 and 16 years are not scattered at random but are gathered into several short intervals at fairly definite periods. Out of 16 cycle lengths between maxima, 9 followed lengths closely similar. In the last hundred years the length has been nearly constant. From these facts we have a good probability that the next maximum will be separated from the last one by the same interval that fell between the last and the one before. This is different from random picking of values between 7 and 16 years as implied in some descriptions of the sunspot variations. Studies have long been in operation to see if we can not find what the sunspot cycle was doing in the last thousand years or more.

Analysis of Annual Numbers Since 1610—Before 1750 the telescopic observations of sunspots were far from systematic. After Galileo's first view in 1610, many views of them were placed on record but there evidently was a great dearth of spots from 1645 to 1715 (Maunder and Spoerer's results). A maximum had probably occurred near 1615, very weak; one near 1626, stronger, and one near 1639, very weak. The full records during the dearth with comments by contemporary observers can be repeated here, after Maunder:

1648–60	often called spot-free.
1649	exceedingly few spots.
1660	spots seen April and May.
1661–70	none seen.
1671	spots seen August and September. Memorandum: "Now 20 years since many spots."

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[1] The sequence takes a form depending on the slant of the analyzing lines: the pattern is inverted but otherwise identical, when the slant is changed from right to left or *vice versa*. Note form also in Plate 15B.

1676	July and August, 3 spots seen.
1677	April, a group visible.
1678	2 or 3 spots seen.
1677–83	almost spotless.
1680	May, June, and August, spots observed.
1681	May and June, spots seen.
1684	Several groups visible.
1686	2–3 groups seen.
1688	several spots seen.
1689	a few spots seen.
1695	after "6 years of no spots," in May we find a "great spot; only great one in 11 years."
1700	November, spots seen.
1704	first occurrences of 2 groups.
1705	at once for 60 years.
1707	2 groups seen twice
1710	January–October spots visible.
October	1710 to May 1713, no spots seen.
1716–21	spot maximum in 1718.

After this, maxima occurred near 1728, 1739, and 1750.

These scattered observations have formed the basis of estimates of maxima on Newcomb's 11.13-year cycle. It is probably safe to accept estimated dates of maxima between 1610 and 1640 and from 1718 on, although they are weighted by Maunder about 2 to 5 in comparison with a weight of 10 for well-observed maxima. Any assignment of maxima during the dearth seems unsafe, since great bursts of spots, even those visible to the naked eye, have appeared in all parts of the cycle, though more likely to occur at maximum. We are convinced that no minima at all can possibly be assigned during that dearth interval, as has been attempted.

When the actual data are placed in a cyclogram as in Plate 15B, we find a good solution for the entire series 1610 to 1930 at 11.2 and another at 11.6 years, giving us a choice of 28 or 27 cycles in that total interval. Each of these solutions appeared in the automatic periodogram of the sunspot numbers made in 1913, Plate 12A.[1] Well-established maxima for the last hundred years give a strong value at 11.4; thus it does not decide between 11.2 and 11.6. If, however, we take the obvious facts of the cyclogram, we find for the series between 1615 and 1788 a solution at about 10.2 comparing very favorably with 11.2 judging by the decreased average residual obtained on applying Maunder's weights to the maxima. These two solutions can be applied to those data and it will later appear that during the dearth a 10-year cycle appears in tree-ring records while the 11-year cycle seems to have failed.

Other Cycles in the Annual Numbers—In the sunspot cyclogram other cycles appear prominently as the tests are carried through a range from 5 to 25 years. After the 10 and 11 year lengths, two others promptly attract attention, 8.5 and about 14 years. They show well by directions of alignment of increased amplitudes as in Plate 15B.

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[1] Published in the Astrophysical Journal, October 1914, and in *Climatic Cycles and Tree Growth*, vol. I, 1919, Plate 9A.

Centers of Mass of Maxima—Cyclogram analysis distinctly uses the mass of maxima in producing its cycle effects. In the case of well-defined maximal masses, as in the sunspot cycle, the use of centers of mass is well indicated, as in the plate referred to. This use of the centers of mass simplifies the general pattern and shows the various lesser cycles, such as 14 years and probably 7.0, 8.5, 10, and also suggestions near 17 and 20. The setting near 23 in Plate 15B shows a symmetrical arrangement of the maxima and one is less conscious of the irregularities in timing near 1800 that looked so large in the 11-year setting. The mean departures from a true period after all are only two to three years, say 20 to 30 per cent of the cycle length, and on a 23-year setting the percentage reduces to 10 or 15.

Possible Half-Sunspot Cycle—In the analysis of the smoothed annual means we do not readily see any half cycle of about 5.7 years, such as found in terrestrial phenomena and reported in radiation data (by Abbot). The form of the sunspot cycle since 1750 with its bulky maxima and very low minima gives apparently no indication of a secondary crest in the 11 years. One finds it hard to look upon the slight hump that sometimes occurs during decreasing spot activity as any substitute for a secondary maximum that would nearly divide the whole cycle length in halves. A secondary maximum of activity in the monthly values would be hard to find owing to difficulties in evaluating the fluctuations during the long low minima, yet, in spite of that, these monthly values seem so far to be the best direct solar data in which we have a chance of finding a 5.7-year period, approximating the half cycle in length.

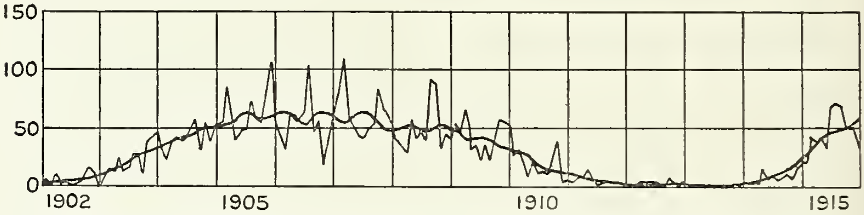

Fig. 30—Monthly sunspot curve to show reduced amplitude at minimum (after Wolfer). Note: This gives a striking illustration of a poor smoothing method

We find, however, in the tree-ring records extensive sequences of a 5.7-year recurrence which we have called the Hellmann cycle; we find also 8.5, 10, 14, 17, 19 or 20, and 23 years, as will appear later. We find also in trees, in the last 1000 years, certain cycles close to 12 years in length (see page 107). Here is, therefore, the place to ask the question: Can we regard such lengths as variants of the well-recognized 11-year cycle? We can not answer yet with certainty, but since sunspot numbers had a limited cycle life at 14 years (1788–1830), we know no reason why 12-year lengths should not occur in the sun.

Analysis of Monthly Sunspot Numbers—In our analysis of the monthly numbers, 1750 to 1934, instrumental limitations lead us to consider cycles of 5 months to 30 or 40 in length. The monthly changes are strong and easily analyzed within each spot cycle while the spots are relatively numerous, but the changes become very weak at the minima. It is difficult to adjust the small changing values during minima in order to place them on a level with the large changes at maxima on a scale suitable for continued analysis over long intervals including both maxima and minima. Nicholson's proposal is excellent: to study each cycle from minimum to minimum. In cyclogram analysis this is done automatically, for the overlapping of two sunspot cycles at the minimum is very slight and can easily be marked on the plot that is analyzed.

For purposes of longer analysis, the changes at minima have to be "standardized." Other students of cycle analysis will recognize this need and the dangers of its application. In our rapid cyclogram analysis it has been possible to try several processes. In the first attempt, the smoothed annual values were subtracted from the monthly values. This was not satisfactory because it left the fluctuations near sunspot minima practically invisible. In the second attempt the monthly values were divided by the smoothed annual means, thus "standardizing" the curve into monthly percentage departures from annual smoothed means taken as unity. But this raised the changes at minima to enormous size, obviously a serious exaggeration. So since we merely wish to make the minimal changes large enough to have an importance of their own but not an equality with the changes at maximum, we have used a process in between the two described; we have taken the monthly values in their original form, added 10 spot number units to each one, and then divided by the mean smoothed line, also with 10 units added, and have plotted the results. This has been found to keep the minima subordinated without concealing their changes.

The results obtained represent my own analysis made about 1918, further examined in 1922 and repeated recently, and Mr. Schulman's independent results obtained recently. Plate 18 gives the data in cyclogram form. From the analyses we discover several things. Some cycles do pass unchanged through the minima but cycles also seem to start and stop with a slight preference for maxima and minima. A crude analysis was made of the times of starting and stopping (crude because these times are not well defined) and many beginnings and endings seemed to occur in a 10-year cycle with occasional cutting to five years. Caution is needed in attaching significance to this result.

Cycles found in the monthly sunspot numbers may be condensed into a frequency periodogram as in figure 31c, where the various monthly values are brought together for comparison with radiation and other changes studied below. The following table gives the data regarding them.

Cycle Length and Duratiyn: Monthly Sunspot Numbers[1]

Cycle length, mos.	Underl.[2]	Duration
	1749.5–1780	
5.7	no	1756.5–61.
6.0	no	67.5–80.
7.6	1	70.5–80.
8.3	1	51. –57.
10.4	1	49.5–53.5
10.4	2	66. –71.5
10.4	x	74. –80.
11.2	no	57. –62.
13.0	x	69.5–80
13.6	2	51.8–56.
13.6 (oc ½)	no	61. –74.5
17.0 (much ½)	1	49.5–57.5
17.0	x	69. –75.
24.5 (oc ⅓)	no	49.5–80
27.1 (all ½?)	no	49.5–80.
	1770–1815	
5.5	no	1793.8–03.
7.6	1	70. –81.
8.9	no	85. –91.
10.5	no	91. –15.
13.6	1	95. –15.
17.5	no	85. –05.5
27.0	1	70. –15.
	1805–1850	
6.9	no	1805. –25.
7.5	1	35.5–50.
8.0 or	1	22.5–43.
11.0	2	24.5–36.
13.5	no	08. –30.
15.0	1	36. –50. (phase change at 1841±)
19.2	x	05. –25.
24.6	no	10. –45.
27.7	no	05. –50.
	1840–1885	
5.7	no	1852.8–75.
6.7	1	76. –85.
7.9	1	40. –45.
8.3	1	50. –85.
11.2	no	69.5–82.
11.4	2	51. –63.
13.8	no	65. –80.
14.1	no	40. –65.
14.5	1	40. –49.5
16.7 (oc ½)	2	50. –85.
17.9 (oc ½ oc ⅓)	no	51.5–85.
27.0	x	40. –85.
	1875–1915.5	
6.1	1	1908. –15.5
6.7	1	1875. –84.5
7.6	1	1903. –08.
7.8 and	1	1880. –96.5
8.1 or	1	98. –03.7
7.9	1	80. –03.
8.8 (much ×2)	no	1909. –15.5
10.8	x	1875. –15.5
11.9	1	89.5–95.5
12.3 (much ½)	no	96.5–15.5
12.6 (oc ½)	no	75. –88.
15.6 (oc ½)	1	75. –86.
17.2	x	75. –15.5
17.9	1	1907.5–15.5
25.5 (oc ½, oc¼)	no	1875. –15.5
26.7	x	75. –15.5
	1905–1934.5	
5.1	1	1926. –31.5
6.1	1	05. –14.5
6.5	no	20.5–28.5
7.2	1	31. –34.6
8.2	1	05. –11.5
8.2	1	18.5–22.5
8.2	no	22.5–31.5
9.9	1	15. –24.–
10.2 (½)	1	24. –34.6
14.4	no	05. –34.6
15.7	1	05. –31.5
17.1	2	05. –34.6

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[1] Table prepared by Mr. Schulman.

[2] See page 146 for meaning of underlines.

Thus we find consistent cycles as follows: 6.8 months, weak; 8 months, very strong; 11± months, strong; 13.5 to 14 months, strong; 16 to 17+ months, strong; 25 medium 27 months, strong.

ABBOT'S RADIATION MEASURES

The heat reaching us from the sun can be measured by the rate at which it raises the temperature of water or silver or other substances suitably blackened and presenting a known area to the sun's rays. Built on such a principle, the bolometer invented by Langley and improved by Abbot and the silver disk pyrheliometer invented by Abbot have enabled us to secure since 1918, and to some extent before, exceedingly accurate measures of the amount of heat coming from the sun to the outside of our atmosphere; as well as the amount absorbed by our atmosphere, in a few favorable locations, and the amounts reaching the ground. The intensity at mean solar distance, outside of our atmosphere, is known as the "solar constant" and its average in standard units is usually given as 1.94 calories per square centimeter per minute.

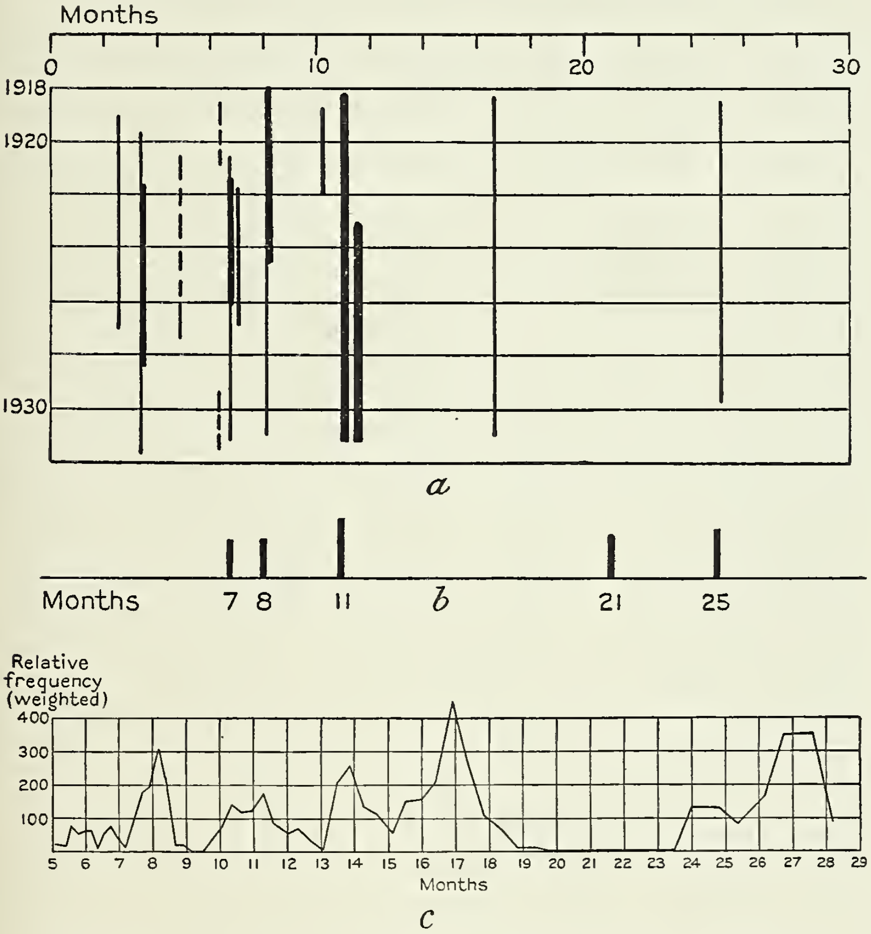
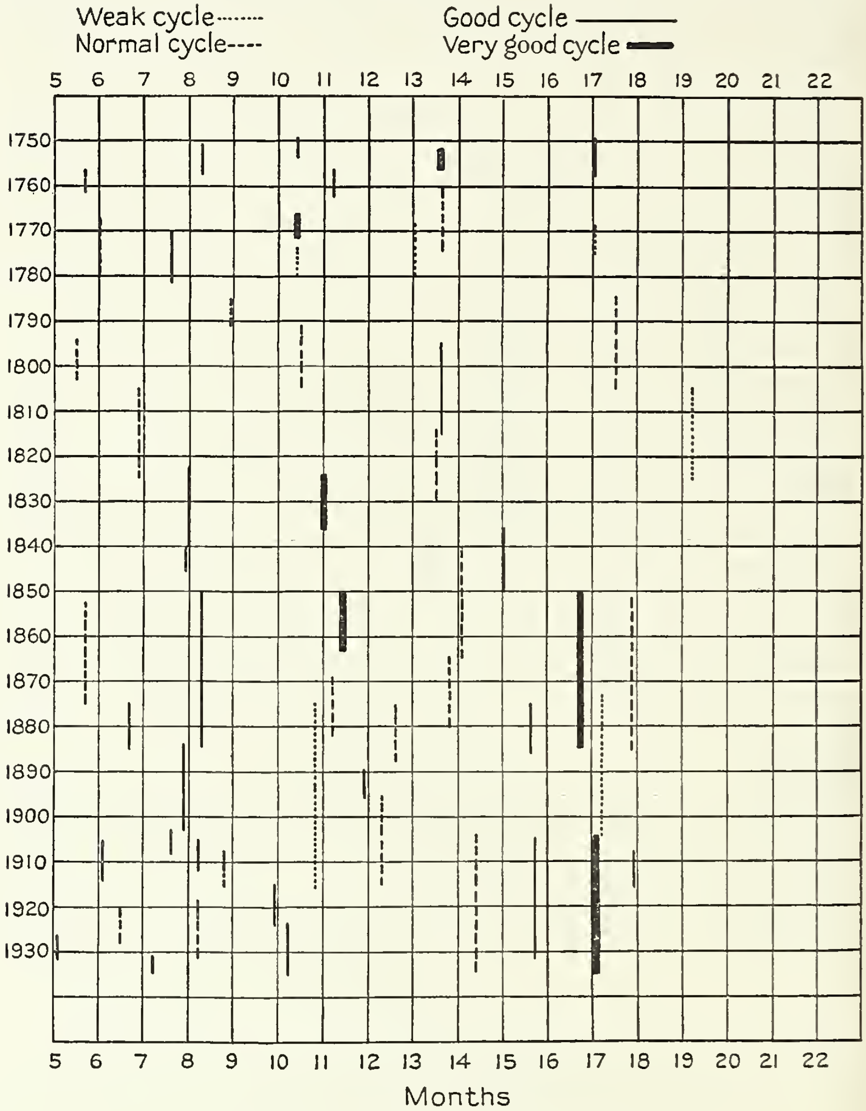


Fig. 31—a. Chrono-periodogram of Abbot's radiation curves analyzed by cyclogram methods.
b. Abbot's cycles in same.
c. Frequency periodogram monthly sunspot numbers, 1750–1934.

Abbot, who is unquestionably the highest authority on solar radiation, has made cycle analysis of his monthly values using an instrument of his own invention, the periodometer. This instrument is especially good at cycle summation and subtraction. His cycle lengths are first estimated by eye from the original curve.[1] By this form of integration he can test esti-



d

Fig. 31—d. Chrono-periodogram of same.

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[1] The periodometer has the data set up on a right-hand drum and integrates it by a system of fractioned additions (*i.e.* it finds the sum of each occurrence divided by number of occurrences). This produces on left drum a continuous repetition of equal integrations. Then the integrated values on left drum are caused to subtract themselves from the originals on the right drum. Smoothing may be performed also. (See Bibliography, 1932[3] and 1935.)

mated cycle lengths and he happily gets away from insistence on some special curve of variation, such as a sine curve. His cycles are assumed to continue unbroken through the data but one notes that his "eye" method of finding cycles, just referred to, permits recognition of discontinuity in cycles and hence aids in the selection of preferred data. By his skilful treatment he has brought out the cycles expressed in the accompanying periodogram, figure 31b. On checking his results we found, as he did, a good cycle at 8.0 months, a very strong one at 11.0 months (Schulman put it at 11.2) and possible shorter cycles at 2.5 and 5.0 months and 3.4 and 7.0 months. Our method did not lead us to give weight to our results in longer cycles. Plate 19B shows cyclograms of his original curve (Feb. 1932) at 8 and 11 months.

Abbot's synthetic curve B (see his paper of February 1932) combining 8, 11, 25 months and others longer, gives 8 and 11 months apparently not quite as strong as in the originals. His residuals, C, have apparently no 11-months cycle but still contain traces of 8-months cycle, distorted because the original varied in amplitude. We found evidence of a 13.3[1]-month cycle and Schulman placed a faint cycle at 12.1 months. While no striking resemblance between Abbot's radiation curves and monthly sunspot numbers shows since 1919, using the data as they are, a resemblance may be seen between his radiation cycles and the general periodogram of monthly numbers.

The existence of a terrestrial cycle having the same length as the sunspot cycle but showing two maxima, usually unequal, instead of one, has raised the question: By what physical means could a single-crested cycle in the sun produce a two-crested cycle on the earth? It has been suggested that such a result might happen if a force acting from the sun upon the earth produced an inverted effect when exceeding some critical value. Along this line Abbot, for instance, has found a temporary, strong reduction in solar constant in the presence of an extra large spot. Bollinger has worked out a formula of relation of radiation to smoothed annual sunspot numbers that could produce a "Hellmann" effect or a double-crested resultant curve in radiation to a single-crested original sunspot curve. Clements has observed an inversion of relation between drouths and sunspot numbers when the latter rose in value above 90. Clayton has found reversals of phase in climatic cycles.

We found above that Abbot's radiation study shows cycles strikingly similar to the general periodogram of cycles in monthly sunspot numbers, but that during his observations, 1918 to 1931, the agreement is restricted in two cycles, 7.9 months, a strong cycle, and 25 months, a weak cycle. Inversion of reaction is intimated in some of Abbot's diagrams.

PETTIT'S ULTRA-VIOLET RADIATION CURVES

Pettit's ultra-violet radiation measures show something quite different from Abbot's data. When we speak of heat radiation as measured by Abbot, we include all wave lengths, knowing that most of the heat energy is in the long waves, and that this energy comes rather generally from the sun's surface. The ultra-violet rays measured by Pettit are short waves and have little effect in heating. They are thought to produce changes in ozone and ionization of our upper atmosphere and in plant growth, with other effects upon climate and plants not yet worked out. The proportionate changes from day to day and year to year are far greater in the ultra-violet than in the general heat radiation. And the source of the ultra-violet is doubtless different. The short series of observed data, 1924 to 1931 or later, shows in parts better resemblance between ultra-violet radiation and sunspot numbers than is found between total heat radiation and sunspot numbers.

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[1] Abbot finds a 13.6 month cycle well marked in weather; see Bibliography, 1935. See also his solar radiation analysis therein. See reference to 28-month cycle in I, 106.

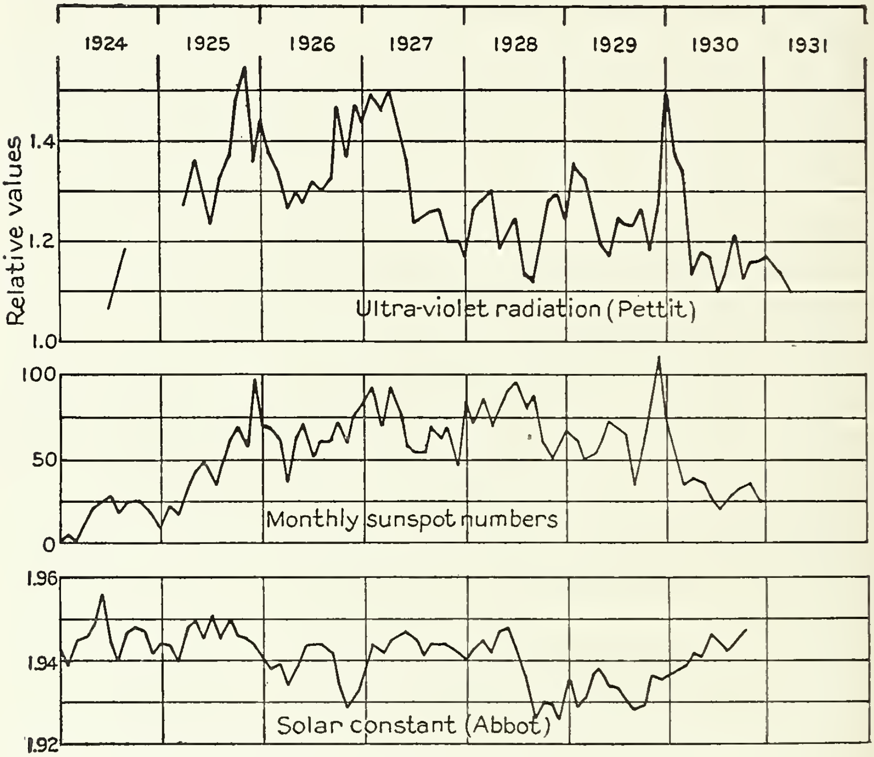

Fig. 32—Ultra-violet radiation compared to monthly sunspot numbers and the solar constant.

This intimates a substantial difference in source and points more directly to the activity in the spots themselves. Pettit has called attention to an interval of possibly reversed correlation from the middle of 1928 to early in 1930. Pettit's curve and the monthly sunspot numbers are compared in figure 32.

INTERNATIONAL MAGNETIC CHARACTER FIGURE C

The International Magnetic Character Figure C, represents the daily "agitation" or rapid irregular changes in the intensity of terrestrial magnetism. Disturbances are estimated on a scale of 0 to 2 and averages made of many stations so that the data may represent widely distributed terrestrial conditions. It is accepted that this phenomenon is due to the sun and yet the exact machinery by which these effects reach the earth's magnetism is not certain. It is probable that streams of charged particles come from the sun from active areas near the solar meridian, but it is also thought possible that there is an effect from short-wave radiation in the form of ultra-violet light. Motion of our upper atmosphere may carry electric charges received from the sun or developed from solar radiation in such a manner that magnetic fields are produced. There is close connection between terrestrial magnetic disturbances and northern lights, earth currents and the so-called magnetic storms that affect telegraph lines.

Magnetic observations extend back to 1906 and in less accurate form to 1872 and in crude form to 1835, and constitute one of the longest sets of precise observations connected with the sun. In some respects, therefore, these data rank very high as source material in any study of periodic values in solar activity and must be included in our list. At the same time they illustrate certain features of cyclogram analysis and open the way to further studies of the sun and its phenomena.

Observers who have made careful studies of periodicities in magnetic data, state that the correlation of magnetic disturbances with sunspot values seems to be low in short time intervals such as the day and the month, but greatly improves as short variations are smoothed out and long intervals (for example, the year) are considered. On the other hand, greatly agitated days (magnetic storms) sometimes come when a large sunspot or group of sunspots is central on the sun. Well-defined periods of about 27 days have been found in the magnetic character figure C. Numerous coincidences with known rotation values lead scientists to accept these periods as measures of solar rotation. There is also in magnetic data a 6-months cycle that can be traced back to 1872. A very minute effect has been isolated, depending on the lunar day (Chapman: 1918).

Solar Rotations in Magnetic Data—One of the productive methods hitherto employed in analyzing the magnetic data is Dr. Bartels' graphic solution in a multiple plot (1932; see Chree and Stagg in Bibliography; for multiple plot see Chapter II) giving daily values arranged in rows as if in a summation process. In this pattern his eye has caught discontinuous periods as mentioned above under that topic. Thus he has confirmed the semi-permanence of the magnetic source areas or M-regions in solar longitudes and at the same time has found some evidence of activity in opposite longitudes of the sun. His later application of probability principles produced his theory of "quasi-persistence." He treats this phenomenon as a general character rather than as a phenomenon localized in time, and yet his summation dial enables him to date some cyclical changes.

In 1935, desiring to compare cyclogram analysis with Bartels' summation dial of magnetic data in which he investigated "quasi-persistence" (fig. 26) we secured the records for 1906 to 1934 in daily values. For convenience these were compressed into 3-day averages.[1] The data could then be compressed again if needed and longer cycles investigated. In the first examination by cyclograph several striking effects appeared at once: the intervals between magnetic maxima easily show several definite periods between 26 and 32 days; a period close to 27.0 days is much more persistent than any other; this is occasionally reduced to 26 days and sometimes is mixed with longer periods of about 30 days. One notes that a synodic period of 30 days in solar rotation occurs near latitude 40° which is at the outer limit of sunspot area. It is difficult to explain how streams of charged particles, leaving the sun in lines nearly perpendicular to its surface, can reach the earth from that latitude; yet one finds possibilities in the curves of coronal streamers often photographed during the total solar eclipse. Periods near 27 days are double-crested; that is, a lesser maximum appears to bisect them as would happen if two magnetic source areas were at opposite longitudes of the sun. The second maximum is often fainter than the other. Near sunspot maximum additional periods make the variations more complex.

The results of cyclogram analysis confirm strongly the persistence or localizing of magnetic source areas in solar longitudes. For example, there seems to have been very little change in longitude of a 27.0-day maximum from the beginning of 1930 to our latest data in the middle of 1935. A 27.0-day period is the one commonly shown by sunspots at 5° to 10° from the equator. Hence we presume that near sunspot minima the source areas persistently active in agitating terrestrial magnetism are sometimes localized for long intervals at that latitude on opposite longitudes of the sun.

Sources of the 6-Months Period—Since the 6-months maxima occur in spring and autumn, the question has been raised whether they originate in the sun or in the earth and the relation of the magnetic maxima to each has been studied. For example, the sun's pole is inclined 7° to the ecliptic in such a direction that in early March the sun's southern hemisphere is most inclined toward us, and in early September, its northern hemisphere. But late March and September are the times of the terrestrial equinoxes and the maxima could be related to them through the changing of the earth's hemispheres regarding exposure to the sun's radiation. An extensive statistical study of the 6-months maxima by Bartels (1932) has demonstrated that the earth is one source of this variation, that is, the magnetic forces from the sun are sufficiently terrestrialized to show an earthly character.

Cyclogram analysis applied in 1935 presented immediately a complex feature. In the vicinity of the sunspot minima and especially in the last one, 1932-1933, the 6-months maxima alternate in opposite longitudes of the sun. This is shown in our diagrams, Plate 19B and C and figure 33. The figure summates the magnetic effects that come while opposite halves of the sun (longitudinally) are presented towards us. If this effect of alternating

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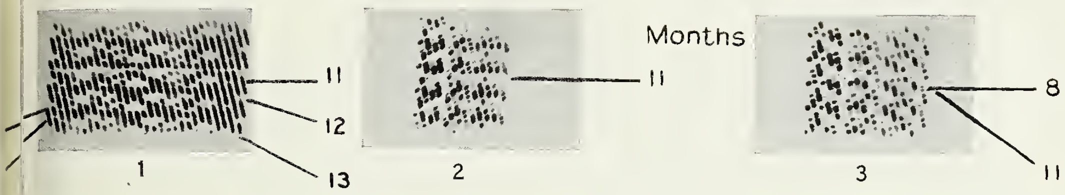
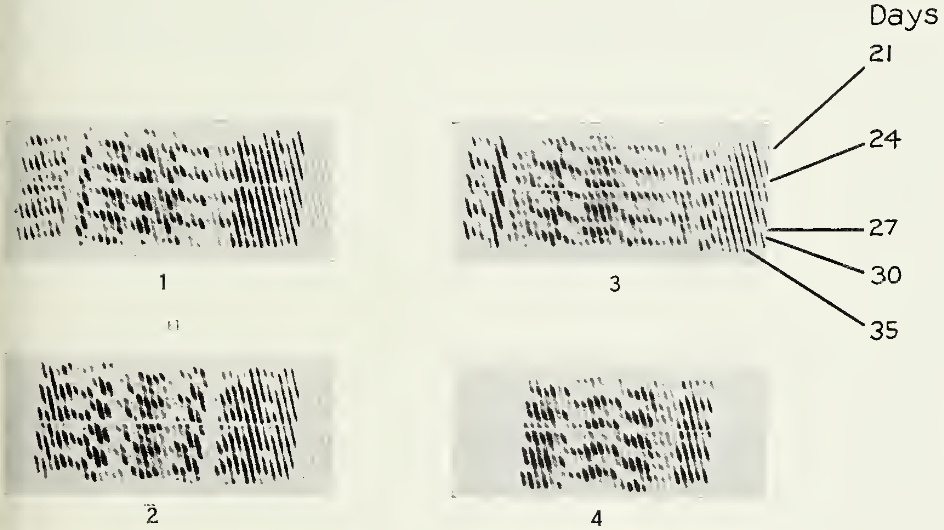
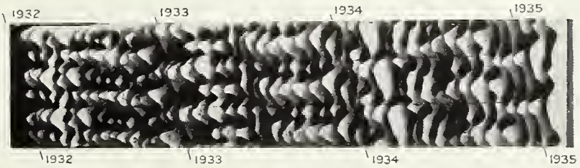
[1] The preparation of these curves was done by Mrs. G. Dewey and Mr. Arthur N. Cowperthwait.



A



B



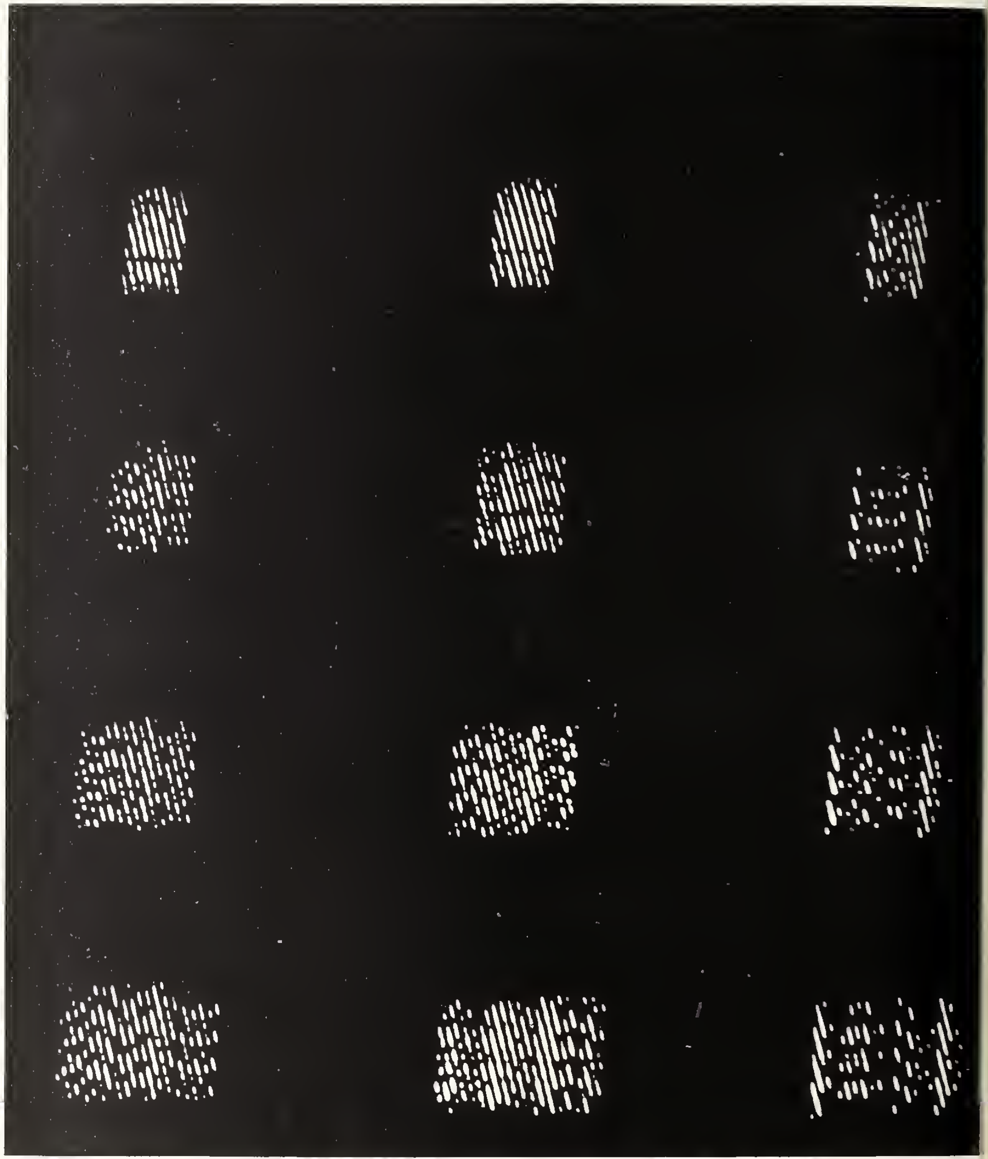
C

A. Cyclograms of Abbott's radiation curve, December 1918–July 1930. 1, Directional values at 11 months. 2, Analysis at 11 months. 3, Analysis at 8 months.

B. Cyclograms of magnetic character figure C, analyzed for 27.0-day period. 1, Jan. 21, 1923–Jan. 26, 1926; 2, Jan. 26, 1926–Oct. 29, 1928; 3, Oct. 18, 1928–Dec. 15, 1931; 4, Dec. 15, 1931–Nov. 9, 1933.

Five stronger horizontal rows indicate a 27.0-day period; intermediate rows show maxima in reversed phase, that is, in opposite longitudes; rows of maxima pointing down to the right indicate periods more than 27.0 days; rows pointing up to the right, less than 27.0 days.

C. Cycle relief map of the magnetic character figure C January 1932 to March 1935. It is made of separate cards cut to contours of 3-day means, slightly smoothed; each card has 81 days of data progressing upward in the photograph and beginning on each card 27.0 days later than the card to its left. Note the conspicuous horizontal alignments and the alternating levels of the 6-months maxima.



Cyclogram test to distinguish between natural sequences, right column, and rand sequences, other 2 columns: natural sequences have fewer short cycles and hence s clearer patterns.

maxima is correct, the sun shares in causing the 6-months maxima. Until this effect is confirmed our results should be considered provisional

Similar caution must also be exercised in drawing conclusions from this apparent relation between the sun and the earth's magnetism Its display in 1932–33 as analyzed in the cycle contours shown in Plate 19C, suggests that these chief magnetic source centers are on opposite sides of the equator and hence diametrically opposite each other at some latitude less than 10°.

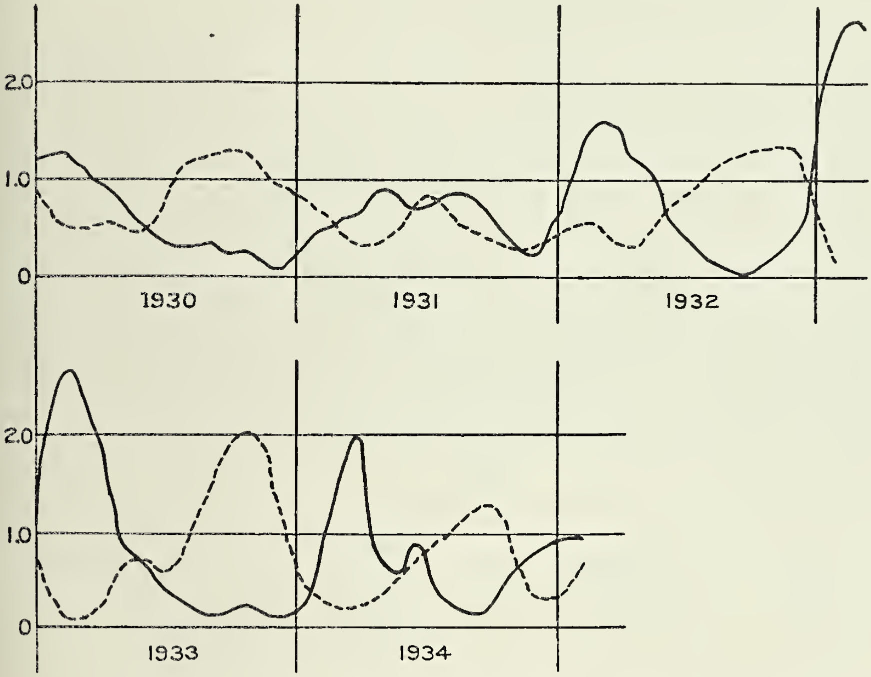


FIG. 33—International Magnetic Character Figure C as related to opposite longitudes on sun during a 27-day period. Note: Means of approximate first halves of successive 27-day periods provide ordinates for one line and means of second halves of same provide them for the other line. Ordinates are relative values on a special scale with unity approximating 0.13 unit of character figure C per day above an assumed base of about 0.5 unit. This shows alternate 6-months maxima as occurring at the time that opposite solar longitudes (near the solar equator) are central as seen from the earth.

Other Periods—In 1931 there was evidence of a 9-day period operating coincidently with those of 13.5 and 27 days. Since 1906 it shows durations of more than four months in the following years: 1910, 1914, 1916, 1924, and 1931. Of these, 1914 exhibits the unusual length of 9.9 days, which is one-third of a long cycle showing in that year. Maxima, possibly alternating in longitude, show at previous sunspot minima, for example, in 1922 and 1923 on a period of 27.0 days; in 1912 and 1913 on a period of 27.3 days. The year 1914 has a period near 29.4 days; 1916–18 give evidence of a possible period somewhat over 31 days; 1918.4 to 1920.9 show a period close under 30 days; 1924 and 1925 do the same. In 1926 and 1927 the common 27-day period seems to become 26 days; this lengthens again to 27 days near the beginning of 1928. Thence it continues for two years and in November and December of 1929 seems to have a phase change of several days, which leads to the beginning of the stable sequences of 27.0 days in the years 1930–35. Altogether we have a very interesting pattern of rotation periods, here stated only in a preliminary way.

NAKED-EYE SUNSPOT RECORDS

Naked-eye sunspots are not infrequent. They may occur at any part of the sunspot cycle but are more likely to be seen near the maximum. Personal experience placed three conspicuous naked-eye spots, one at a maximum (1917), one two years before a maximum (1882), and one two years before a minimum (1921). Each was accompanied by northern lights, especially the last.

Historical accounts of naked-eye sunspots have come chiefly from Chinese records and are quoted by Fritz in connection with his studies of northern lights. His list gives us really only four groups that might supply or suggest dates of maxima. Any well-established date of maximum before 1610 has an important value. These groups are as follows (with observed cycles):

		Intervals	Cycles Years	
1.	A.D.	300–375	10.0	no strong location of maximum: 373 possible.
		370–400	13.8	no strong location of maximum.
2.		800–880	11.1	maximum possible at 840.
3.		1078–1206	8.3	no location of sunspot maximum: 1120 is possible.
4.		1369–1383	10.±	evident sunspot maximum 1370–72.

The second is the weakest of the four but gives rather a clear 11+ year cycle.

RECORDS OF NORTHERN LIGHTS

The other effect of solar activity visible to the unaided eye and forming perhaps a guide to sunspot history is the aurora or northern lights. The data here analyzed have been gathered together by Professor H. Fritz, Zurich, 1893, with a translation by W. W. Reed in the Monthly Weather Review, October 1928. (See Bibliography.) Early records of this phenomenon are necessarily fragmentary. Fritz has taken the descriptions from historical references. These data have been transferred to three cycleplots and analyzed, as follows:

Cycles in Fritz's Auroral Records

Cycle length in years	Duration	Maxima of period named
(1) 434–677 A.D.		
12.4	434–610	577
15.2	all	585
(2) 727–1014		
10.0	727–925	809, 840
(3) 1085–1403		
11.8	all	1096, 1205, 1263, 1349
13.8	1349–1403	1349
(4) 1432–1635		
11.8	all	major max. 1561; lesser max. 1568 (possible Hellmann cycle)

It will be noticed that we have here abandoned the maxima assigned by Fritz in an 11.1 year cycle and endeavored to find maxima that have intrinsic evidence of being sunspot maxima. One might possibly accept A.D. 577 on a period of 12.4 years but might feel doubtful about 585 on a period of 15.2. A.D. 809 and 840 might occur on a 10-year period but they are not convincing at all. A.D. 1096, 1205, 1263 and 1349 on an 11.8-year period seem satisfactory, but a maximum on a 13.8-year period does not seem satisfactory. The 11.8 period from 1432 to 1635, with a major maximum in 1561 and a lesser maximum in 1568 seems to be giving us real information by suggesting a Hellman cycle which agrees with the tree records of northern Arizona and deserves full consideration.

V. ANALYSIS OF TERRESTRIAL RECORDS

Multitudes of attempts have shown that here and there seemingly purposeless climatic variations gather themselves into orderly form and give cycle effects of limited duration. The obstacle which climatologists have everywhere encountered is the short length of the meteorological records; they are far too short to permit a general study of climatic cycles. This difficulty is now being overcome by the use of tree-ring records having a strong climatic correlation. We have a pyramid of ring records consisting of hundreds of trees that cover the last century diminishing to four that cover 3000 years. For all this material we have a flexible and rapid form of cycle analysis.

In this study of climatic variations we seek answers to many questions: What are the cycles that do appear; when do they come; how long do they last; are they of small or large amplitude; do they come over large geographical areas at the same time or only by the acre, so to speak; have they prevailed at other times in the last 1900 years; do they resemble cycles in sunspot numbers or other solar phenomena and how can observations of the sun contribute to the problem; can they be used in long-range prediction?

These questions state the field to which studies in the succeeding pages will be devoted. Attention will be given to the relation between solar and climatic changes and a final chapter will take up the practical summary of this information in an attempt to point out its most important parts contributing to long-range prediction. The remainder of this chapter takes up in a series of topics the most distinguishing characters and problems in ring growth and climatic cycles that have emerged from many considerations of the subject and especially from the use of the cyclogram method of analysis, all introductory to the lists of cycles found.

CHARACTERS OF CYCLES IN RING RECORDS

Discontinuous Periods—Sometimes called broken periods, fragmentary or short-lived periods; sometimes called cycles when their variability is referred to. The word cycle is used as a more general term. Reference is made to their special discussion in Chapter III.

Conservation—Persistence of similar values in two or more successive years resulting in less frequent crossing of the mean in natural sequences than in random sequences, is classed statistically as conservation and should be examined under that heading. When three general curves of western tree growth were examined by Dr. Dinsmore Alter for lag correlation expressed in his correlation periodogram, high correlations were found in short lags of 1, 2, and 3 years. He at once recognized this conservation and asked whether I had otherwise noticed it. I had used a form of it in testing relation of

Prescott ring growth to rainfall and have found it rather general in that relation in the Pueblo Area. I answered that it had been noticed and that it would probably be found stronger in the maxima of tree growth than in the minima. So he segregated the measures of the general Flagstaff area mean curve, FAM, 1780 to 1921, one of the curves already tested for correlation periodogram, into four successive groups extending from the highest value to the lowest and obtained the correlation coefficient between successive years for each group separately. The coefficients were as follows:

	Mean value	r	r/σ_r
Highest 25 p. ct.	1.30	0.42	3.2
Second "	.89	.23	1.7
Third "	.67	−.09	.66
Lowest "	.40	.10	.71

In the highest and lowest groups the correlation was carried backwards to the preceding value with this result:

Highest 25 p. ct.	1.14	0.41	3.1
Lowest "	.58	−.12	.86

He concluded that there is a certainly real positive correlation with the succeeding value in the highest one-fourth of the data and a quite probable correlation in the second highest 25 per cent of the data. The rest show what we should expect from accidental values within the chosen sample.

The reverse problem, that is, the correlation with the preceding value shows, as far as carried, the same result as the forward test. Hence he regarded this as evidence that an unusually good growth strongly indicates a reserve for the following year and also that the preceding year was good. In other words a favorable condition this year can not give the best growth this year if the tree was weakened last year.

Triangle Tests—These are tests for the purpose of distinguishing between random and natural sequences. Three curves are prepared, one giving the original data and the other two showing the same set of values drawn by lot. Attempts were made to select the genuine record from the random records by some obvious character in it. Some twenty different growth curves averaging 150 to 175 terms (yearly values) in length were tried and in every case correct selection was made. This success, we recognize, was due to conservation in these natural sequences.

Two basic methods of choice were used: smoothing and periodogram methods. In trying to pick out the genuine from two random curves by the first of these methods, each sequence is smoothed by longer and longer running means; the one that most reluctantly becomes a straight line is likely to be the genuine. In this treatment we observed a significance in another character: namely, that natural sequences, the longer they are, show longer and longer cycles[1] (fig. 34).

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[1] If a number of group curves are tested at the same time, many of the genuine can be picked out from the group by similarity of appearance, for they cross-identify and the random sequences do not.

The periodogram test has been tried out more thoroughly than the other. The three sequences were made into cycleplots and at four different cycle lengths settings were made on each and cyclograms secured and printed on plates, three at a time in an order unknown to me. That made 80 sets of 3 patterns each. The correct choice was made of the genuine in every case simply on the basis of relative freedom from short cycles. Three sets (15 per cent) were difficult, and the choice held somewhat uncertain. The tests also show the domination of longer cycle lengths in natural sequences. This character may be stated in periodogram terms by saying that the frequency periodograms of natural sequence have a level or upward trend, while those of random sequences have a downward trend. These conditions make it rather evident that short random sequences of 50 or 75 terms become very difficult to distinguish from real ones; and that was found to be the case.

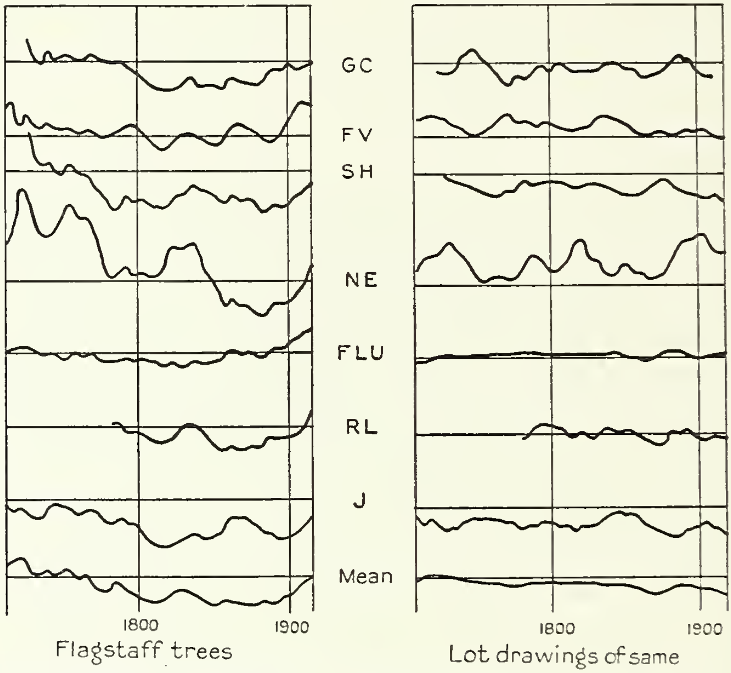

FIG. 34—Effect of smoothing on natural sequences (left) and random sequences (right). Flagstaff area—20 year running means

These two types of triangle tests are illustrated in figure 34, giving an example of smoothing; and Plate 20, showing the cyclogram test. In the latter the right column is genuine.

Clough has referred to a similar character in natural sequences by observing that in random sequences the curve crosses the mean line more often than in natural sequences.

Similarities over Areas—In establishing the chronological identity of rings in different trees, we are at the same time proving the climatic similarity over the terrain involved. Climatic similarities, however, must be supported not merely by a corresponding deficient ring here and there but by the average degree of resemblance in all rings used. In addition to the closeness of resemblance, we are interested in the size of the area over which it exists. Such areas of similarity in ring growth constitute meteorological districts. Experience has shown that when cross-identity is perfectly evident within a group of trees, we can be confident that the correlation coefficients between each one and the others are high. A mutual correlation coefficient of 0.85 ± 0.02 was found in five Prescott trees having hundred-year records (see fig. 2). Climatic similarities have been tested also by similarities in cycles. (See Reports of Conferences, 1929.) Similarity in three cyclograms, shown in 1928 (vol. II, Plate 9: 1, 2, and 3), joins Flagstaff to the areas near Aztec, New Mexico, 225 miles away. The trees of these regions we already knew had strong cross-identity. In the Flagstaff area the cycle similarities were sufficiently pronounced to date correctly unknown fragments, 125 years long, of records in local trees, in three cases out of four by cycles only. Such dating depended on a well-defined distribution of certain cycles in succession. In trying to date unknown fragments, 200 years long from Flagstaff, by comparison with 2000 years of sequoia records, 50 per cent were dated correctly by cycles. This 50 per cent is far higher than would be the case in random results. It would be conservative to say that the chance of dating in random sets would have been not over 5 or 10 per cent.

Now that we have extended the Arizona ring sequence back to A.D. 11, it has become possible to match one locality against another 600 miles away through many centuries, and we perceive resemblances which will be described below.

Different sub-groups of the coast redwood have been compared by periodograms which show evident similarity and a correlation coefficient of 0.56 ± 0.08; sub-groups of the Central Pueblo Area compared in this way gave a correlation coefficient of 0.76 ± 0.05; random data compared in similar manner show no correlation (0.02 ± 0.12).

Recurrence of Cycles in Past Time—Fully dated tree-ring records have been extended, in California sequoias, 3200 years; and in Colorado Plateau pines and firs, 1900 years. These will be discussed later in the chapter.

Periodogram Resemblance to Solar Cycles—The last item to be listed here forms the subject of the following chapter.

PROBLEMS

Representation of Cycles—Cyclogram analysis was first used in 1913 by the multiple plot and in 1914 and 1915 by cyclograms. Since then its use has been continuous. Until 1918 the best method of representing a group of cycles was supposed to be the periodogram. In the reconstruction of the analyzing instrument in 1918 the automatic periodogram was the goal. Photographs which realized that end were made and published in Volume I.

Then the periodogram, after a trial on variable star solutions (Appendix), was allowed to lapse. In the next reconstruction of the instrument in 1920 under the name of the White Cyclograph, the periodogram part was not included.

The manner of reporting cycles has progressed, but each stage had followed some time after the changes in the observing process. Until 1912 or even later, summated or integrated curves were used. In 1914 the Eberswalde results were given in extended curves with a parallel comparison curve of sunspot numbers (Huntington, *The Climatic Factor*). In 1919 considerable use was made of parallel comparison cycles, which were usually plotted in the original diagram by a "templet" made out of cardboard. In 1921 and 1922 a large piece of analytical work was done on the sequoia records of the last 500 years, as a study of the relation of cycles to topography. No way was apparent for stating these results in detail, and they never have been so reported, although the effect of that investigation appeared in studies of environment (vol. II, Chapter VIII, p. 103) in 1928.

The cyclogram itself as a method of reporting appeared in a single plate or two in 1919 (vol. I, Plate 12, called differential pattern) and in 1928 (vol. II, Plate 9). It was presented in the hope that some would study it and realize its efficiency.

It is difficult to reproduce by photography the details and precision that are apparent in the action of the instrument itself. So in Volume II (1928) the very considerable analyses of the 42 western groups were reported in descriptive paragraphs that told something of the background of the results, such as the location and its topography, the aid obtained in preparing the curves, and the cycle lengths and weights observed. The beginnings and endings of these discontinuous periods were often observed, but as all the analyses were done by the writer, it was impossible to observe and place on record such additional detail in any complete form and it was generally omitted.

But in this reluctance to use cyclogram demonstrations, there was probably a different factor present in the writer, as well as in others. The fact that these cycles are short-lived was seen from the start of cyclogram analysis in 1914, but the greatness of the break from the conception of permanent cycles, or periods, was not really appreciated until 1932, nor the tight hold which the idea of permanence had upon the most enlightened students. Hence the present need of more detailed reports of these cycles, including especially their time of duration. It is hoped that later reports will contain a generous use of cyclograms, but some of the problems of their publication are not solved yet. Hence at present this analytical work is reported below in a tabular form.

The analyses here presented were made extensively by Mr. Edmund Schulman and compared minutely with those of the writer as performed at other times and for other purposes. Some cyclograms will be given to show how that form of presentation can be worked out for more extended use another time.

The Individual versus the Group in Cycle Analysis—A group of tree records represents a geographical locality which may extend from an acre to a square mile or more. Whenever averages of such tree records are made, it means that the trees in the group cross-identify in the spacing of well-characterized rings. Therefore we recognize three methods of reaching a result for the group: (1) Analysis of individual records followed by a frequency periodogram combining all the results (see fig. 35c); (2) simultaneous (or concurrent) analysis of the individuals (described on page 47) and (3) analysis of the mean curve of the group (35a). This last was the method used by the writer in previous published reports. Methods (2) and (3), simultaneous analysis and mean curve analysis, being single analyses result in sharply defined cycle lengths as compared to (1), which consists of analyses of many individual curves and the frequency periodogram combining them. In method (1) there are usually scattered individual values intervening between the obvious maxima, which have the effect of smoothing the periodogram to some extent. We feel that any one of the three methods gives results within the required order of accuracy. In the reports below, the mean curve method (3) is taken as a standard; that is, it has been applied in every case, but many cases have been checked by one or both of the other methods.

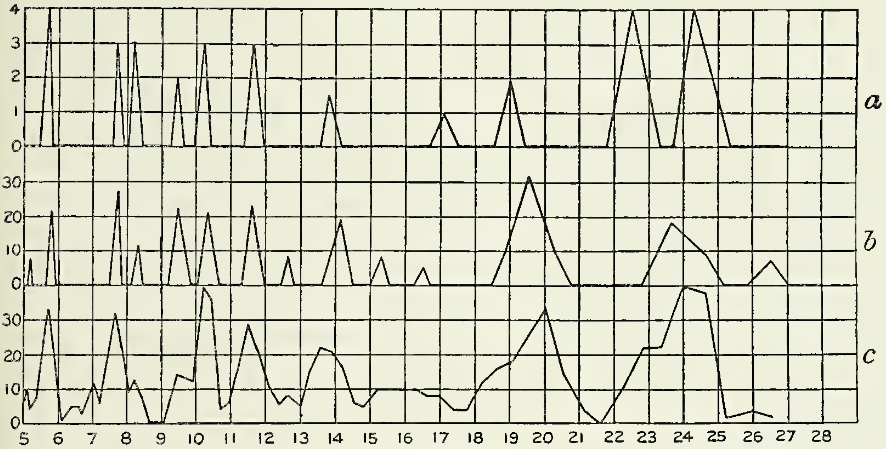

FIG. 35—Frequency periodograms by three processes applied to the same data (Central Pueblo Area; 15 groups—73 trees).
a. Analysis of one final mean curve.
b. Simultaneous (concurrent) analysis of 15 curves taken in 2 sets.
c. Combination of separate analyses of the 15 curves.

The Two-Year "Scatter" Cycle—In short cycles of the order of two or three years in length, we find the maximum difficulty in separating significant from non-significant cycles, for in a curve of random data, cycles of two or three terms (usually years in our tests) are most frequent, and the frequency diminishes as the length increases. Hence we present here some studies of the Two-Year "Scatter" Cycle. This cycle has characters that make us feel that it is not to be regarded as a random effect whose variations will never be explained. The writer made studies of it in 1913, calling it the "2-year zigzag." This has been referred to in volume I, page 106, and in Astrophysical Journal, vol. XLI, pages 180 to 186.

This short cycle, or zigzag, is of the highest importance in cross-identification and in mean sensitivity, and it has influenced the development of methods of analysis because of its great amplitude. Analyses were tried extensively upon unsmoothed curves, but resulting cycle lengths came too often in exact multiples of one year (the unit used) and this was recognized as an error. Resort was made to a form of smoothing which would least distort the general march of the data, and that was the Hanned curve, as explained above.

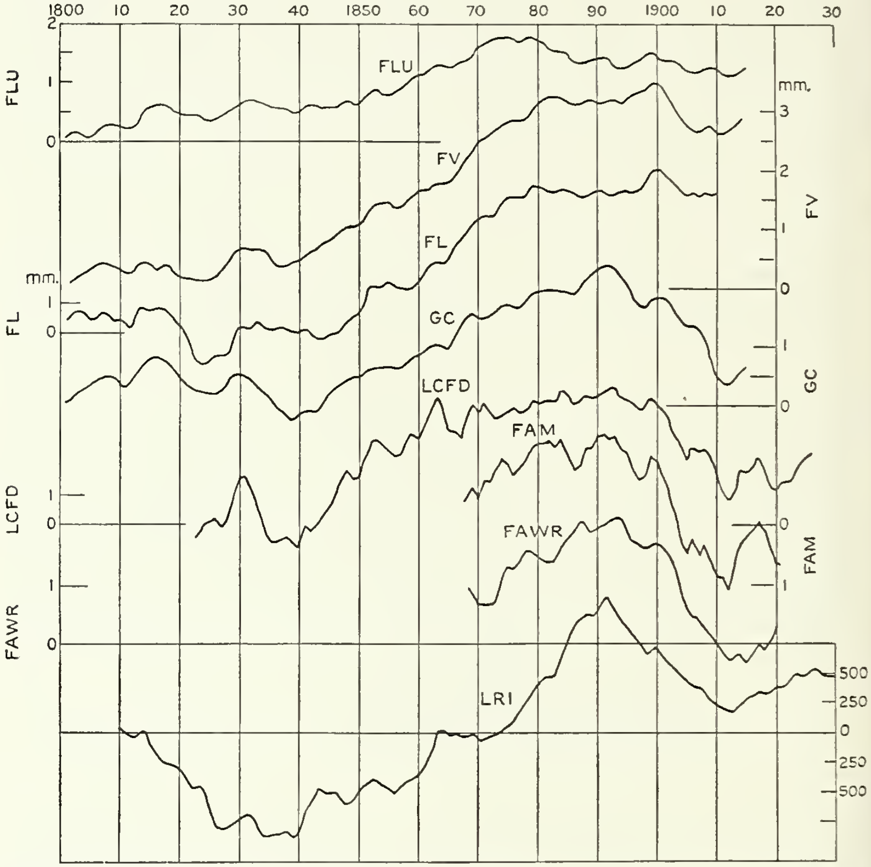

FIG. 36—Two-year reversal test, to show similarity in Arizona area in short cycles. FAWR is Pueblo area winter rainfall; LRI (Lynch's Rainfall Indices) applies to southern California. Note: For example, the general rise toward 1900 and the minor crest at that date.

Next it is recognized that mean sensitivity, or the percentage variation from each ring thickness to the next, is very largely a measure of the amount of this two-year zigzag. Three degrees of mean sensitivity have been shown in previous publications, 11 per cent in complacent sequoias, 35 per cent approximately in the sensitive sequoias, and about 65 per cent in the sensitive yellow pines of Arizona. It is a matter of investigation to find which of these most nearly represents the percentage variation of rainfall from year to year and what are the topographic features that bring the best climatic reaction. Of course, we know that the more sensitive reactions occur near the forest border when the trees are growing under the stress of dryness.

But mean sensitivity is also a measure of cross-identification, and we see that the two-year zigzag is strongly responsible for cross-identification and all the important resulting operations in climatic history and chronology building. Viewed from the opposite direction we see that cross-identification, which we have used widely since 1911, indicates the presence and fair uniformity in action of a two-year cycle over a large area. Since the two-year zigzag, or scatter cycle, covers considerable areas with uniform results, it is not a mere random local effect.

Our present method of re-observing these facts is the same method used in 1913; namely, taking the increments with signs plus or minus, from year to year, and reversing alternate signs and making a mass plot of the continued algebraic sum of the resulting values. And we discover, as could have been expected, that the two-year cycle is very uniform over each of the three western zones taken by itself. For instance, figure 36 shows the mass curves from several locations in the Arizona zone. Here we get a fairly uniform general effect of the rising curve in the last 125 years to a maximum in 1880 to 1900 and a descent thence to the present time, and a series of minor crests in this general curve at average intervals of 5.2 years. The latter are grouped for comparison in figure 37. This 5.2 years becomes a beat or interference effect between an exact 2.0-year cycle artificially produced by reversing alternate signs and a cycle of either 3.23 years or 1.44 years. Hence such an interval may be due to a cycle in winter precipitation of either length given.[1]

On examining in the same way the Coast Zone and the Rocky Mountain Zone we find for each a similar effect. These three results have good agreement between 1850 and 1900, but before and after that the agreement is poorer. This zone summary is shown in figure 37b. Figure 38 shows the same process applied to random data.

One naturally inquires whether this two-year cycle could be due to some solar source. The sunspot cycle has been very stable since 1833, and some harmonic might produce an effect. Clements has attributed this short cycle to short cycles in monthly sunspot numbers. On the other hand, it may be terrestrial in origin and result from some oscillation in ocean or atmosphere. In any case its explanation is greatly to be desired.

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[1] An attempt is being made to locate one or the other of these cycle lengths in monthly rainfall values, but the interruptions produced by the short winter rainy season necessitate careful compensations which are not yet finished.

But another situation makes such study imperative—the prediction problem. Without a real knowledge of the two-year scatter cycle we can only use longer cycles for estimating the future. These are obtained from Hanned curves, as explained, from which the two-year cycle has been extracted by smoothing. After such extraction our smoothed curves show very high correlation, 85 per cent, with similarly smoothed records of winter rainfall. Hence prediction by cycles thus obtained can apply only to a similarly smoothed curve and without the two-year cycle we can only try to predict what amounts to the averages between successive years. Hence the lack of

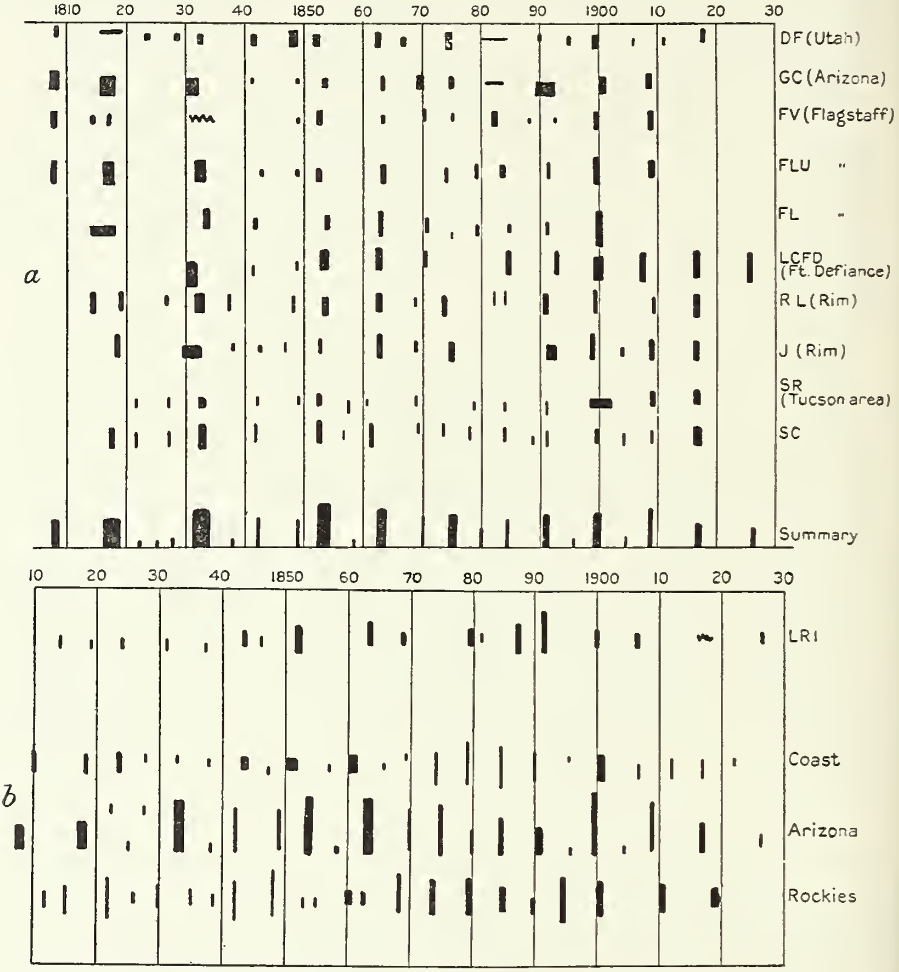

FIG. 37—"Reversal" tests for short cycles.
a. Lesser maxima in two-year reversal test; showing agreement. between groups in Arizona area.
b. Two-year test; lesser maxima summarized for three western zones.

a real two-year cycle analysis is a conspicuous weakness in any prediction plan.

Whether we do or do not identify the exact cycles involved in this two-year variation, we must at least examine the probabilities in the case to see if we can make use of them in the meantime. We can bring together some statistical data on this point through studies of conservation in harmonic analysis as in Dr. Alter's correlation periodogram. In working over some ring records for me, he found high correlations between each value and the next following. At first thought that seems not to agree with the idea of the "zigzag" or two-year reversing cycle. So I have made use of scatter diagrams to bring out the relationship between each annual value and the next following.

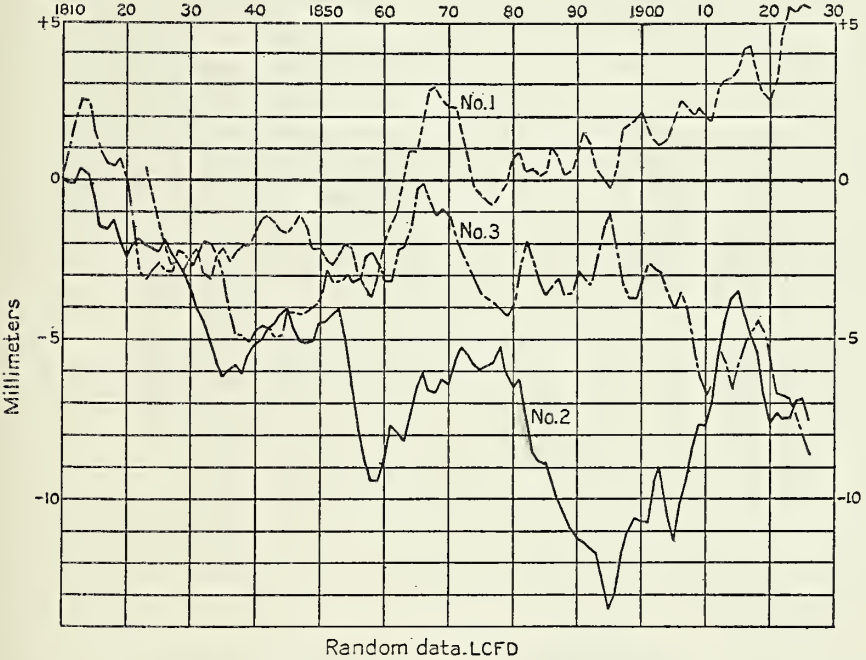

FIG. 38—Two-year reversal tests on random data.

Figure 39 is a scatter diagram to show the relation between successive values, whether quantities above a constant base or departures from a constant mean. Here we have an obvious positive correlation in the evident oval of relationship extending up to the right at 45° inclination. If, however, we take the departures from a Hanned curve, such as we use in cycle analysis—in short, if we take the plus and minus values discarded when we smooth the curve for analysis—then we get figure 40a, which has an oval cloud of dots whose major axis extends up to the left at 45° or at right angles to the former oval and indicates a negative correlation between successive values. This changed major axis indicates in the discarded residuals a strong zigzag that we need so much for prediction purposes. The axes of the oval have a ratio one to the other of 2.3:1.0 and suggest a negative correlation of about 75 per cent between successive departures from the smoothed curve.

Information obtained in the last paragraph is important for prediction purposes. But in using it we must not forget that random data treated in similar manner always give theoretically a ratio over unity. Quoting Dr. Bartels, we may have a series of random values, but the differences between those values are not entirely random, and if we smooth the data as usually done, there is increased chance that successive values will be on opposite sides of the smoothed sequence. In a scatter diagram of such random relation, the theoretical mean form of the oval should have a ratio of axes of 1.3:1.0. Therefore, to retain a clearer estimation of the situation we have added three curves of the two-year reversal interference test on random values in figure 38. They show no relation to each other and thus are very different from the action of natural sequences in our western zones. We

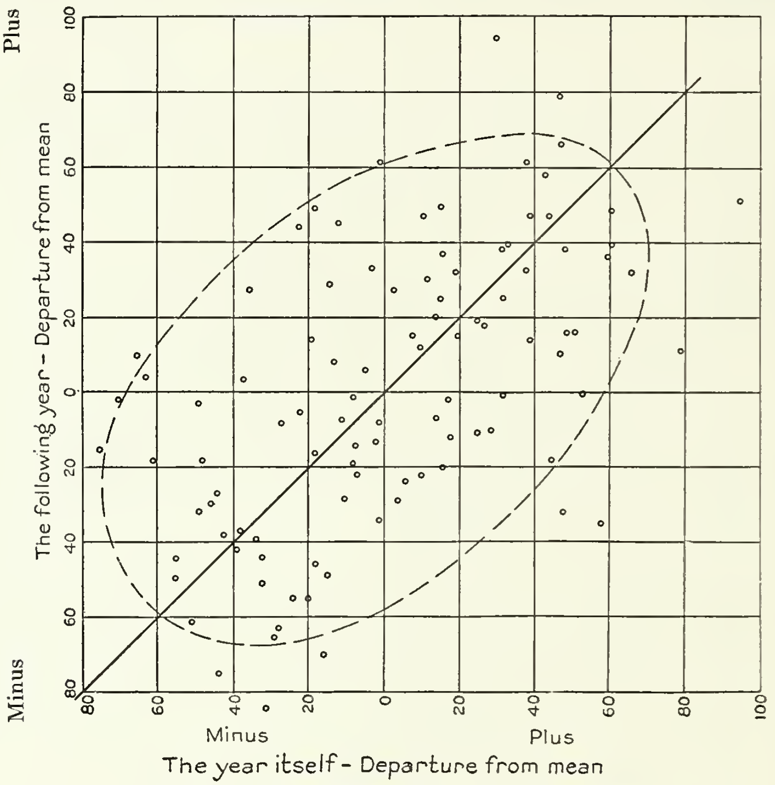

Fig. 39—Conservation in successive years in Fort Defiance group, shown by scatter diagram using departures from a mean

have also prepared a scatter diagram of relation between successive departures from a Hanned mean of random values in figure 40b, which gives a circular cloud of dots and therefore is without indication of negative correlation in successive values.

The solution of the two-year cycle with its difficulties of distribution about the earth has a reasonable chance of being successful; we have now an idea of its general action, and by prediction on the basis of short cycles and then applying the probable residual derived from the inclined axis of figure 40a, we reach the most probable value at this time available.

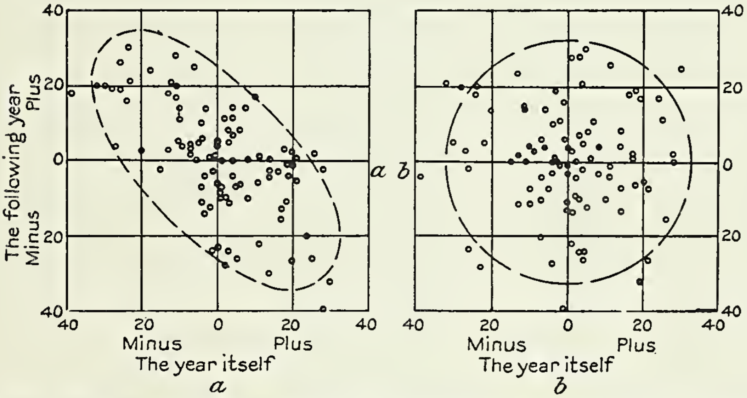

FIG. 40—Successive year conservation in departures from a smoothed curve, Fort Defiance group (a) in natural data; (b) in random data. Same scale as fig. 39.

CYCLES IN 42 WESTERN GROUPS

The groups here listed are indicated by the letters used in the former report, Volume II, *Climatic Cycles and Tree Growth,* Chapter VII, to which reference is made for details of location and collection of specimens and reduction of data.

The assignment below of exact values in cycle length has seemed advisable in order to show the figures on which amplitudes have been computed. Remembering that cycle lengths are subject to errors of 1 to 3 per cent, the reader will be able to find identity in many of these that differ less than this percentage. The cycle lengths given here are used to form the periodograms, figure 41. In these tables the underlines may be taken as nearly equivalent to weights. The rows, also sometimes called "sets," are the number of repetitions of the cycle length. The second and last columns refer to the summation curves in the appendix (see p. 155). Some of the results here presented will be slightly modified after subtracting dominating interfering cycles. It should be recognized that this is the first attempt to group a large number of discontinuous periods together. We expect that more experience will show better how to do it. Therefore we must regard this as a series of

42 Western Groups[1]

Strong Cycles									
Curve	Number	Cycle	Under-lines	Duration	First max.	Rows	P. ct. Amp.	A. D. ratio	Vertical scale
BMH	14	8.7	1	1622–1691	1628	8	15		0.4
AE	6	7.7	1	1740–1916	1747	23	10		1.0
	16	9.7	1	1723–1916	1724	20	7	1.02	1.0
C	9	7.9	1	1778–1920	1779	18	9	1.15	1.0
	73	22.3	1	1780–1913	1793	6	16		0.4
HNT	56	18.6	2	1828–1920	1840	5	19	1.50	0.4
	74	22.3	3	1675–1852	1680	8	23	1.55	0.4
	92	33.3	1	1655–1920	1673	8	18		0.4
Y	13	8.6	1	1755–1917	1758	19	4		1.0
	20	10.0	1	1700–1789	1709	9	7	1.25	0.4
	52	16.9	2	1752–1920	1769	10	11		0.5
	78	23.6	1	1764–1917	1772	6½	11		0.4
LNT	65	20.2	1	1644–1916	1652	13½	9		0.4
CC	19	9.9	1	1742–1840	1746	10	13	1.57	0.2
	22	10.1	1	1840–1920	1847	7	9		0.4
	51	15.3	1	1737–1920	1746	12	13		0.4
BES	35	12.3	2	1775–1909	1779	11	10	1.38	1.0
SF	21	10.0	1	1824–1913	1827	9	10	1.41	0.4
	97	37.0	1	1752–1918	1755	4½	25		0.2
BML	26	10.5	1	1700–1909	1700	20	6		1.0
	82 or	24.7	1	1716–1875	1721	6½	15		0.4
	77	23.4	2	1700–1910	1722	9	21	1.45	0.4
PPT	1	5.8	1	1738–1917	1739	31	1		1.0
	30	11.6	1	1738–1911	1739	15	3		1.0
	54	17.4	1	1738–1911	1745	10	6		1.0
	100	42.0	1	1738–1905	1750	4	16		0.5
LW	2	6.2	1	1759–1919	1760	26	4		0.4
	28	11.3	1	1759–1916	1768	14	10	0.97	0.5
	93 or	33.5	1	1758–1924	1769	5	30		0.5
	96	35.0	1	1765–1904	1768	4	34		0.2
ST	17	9.8	2	1754–1920	1765	17	7		0.5
	64	19.8	2	1743–1920	1756	8½	13		1.0
BDF	10	7.9	1	1782–1915	1788	17	8	1.42	1.0
	18	9.8	1	1782–1918	1787	14	7	0.95	1.0
	59	19.0	1	1826–1920	1839	5	20		0.4
SR	75 or	23.0	2	1670–1921	1677	11	21	1.45	0.4
	72	21.6	2	1673–1845	1681	8	27		0.4
	87	27.2	1	1673–1835	1676	6	21	1.02	0.4
SC	50	15.2	2	1567–1657	1571	6	20		0.4
	91	31.7	1	1567–1820	1575	8	20		0.4
	95	34.9	1	1660–1920	1670	7½	21		0.4
PNL	84 or	26.7	1	1792–1911	1799	4½	37		0.4
	88	27.2	1	1765–1914	1772	5½	31		0.4
RH	24	10.2	1	1860–1920	1867	6	12		0.5
	46	14.3	1	1760–1916	1766	11	10	1.49	0.4
DF	61	19.3	1	1760–1913	1773	8	12	1.67	0.4
	15	8.8	1	1717–1918	1722	23	2	0.69	1.0
SH	5	6.8	1	1744–1920	1750	26	4		0.4
	38	13.4	3	1717–1917	1718	15	22		0.2
	57	18.7	2	1753–1902	1756	8	32		0.2
	86	27.0	1	1717–1919	1718	7½	32		0.1
	98	37.0	3	1717–1920	1720	5½	54	1.44	0.1
RL	11	8.0	1	1770–1913	1772	18	6	1.11	1.0
	60	19.2	2	1770–1903	1774	7	27	1.53	0.4
	99	38.5	2	1770–1903	1791	3½	44		0.2
FLH	42	13.5	1	1768–1915	1771	11	8		0.4
	63 or	19.5	1	1768–1903	1772	7	12		0.4
	67	20.4	1	1680–1924	1689	12	13		0.4

[1] For column headings see pp. 154–156.

42 Western Groups—Continued

Strong Cycles—*Continued*

Curve	Number	Cycle	Under-lines	Duration	First max.	Rows	P. ct. Amp.	A. D. ratio	Vertical scale
FLU	44	13.6	2	1755–1917	1758	12	11	1.54	0.5
	68	20.5	1	1755–1917	1767	8	13		0.4
	89	27.3	1	1700–1917	1717	8	13		0.4
J	80 or	24.1	2	1760–1916	1770	6½	36		0.4
	83	24.8	2	1655–1902	1668	10	24		0.4
NE	29	11.5	1	1751–1922	1759	15	20	1.72	0.4
	45	13.6	2	1755–1917	1757	12	15	1.10	0.4
	58	18.7	1	1755–1922	1759	9	26	1.66	0.4
GC	49	15.0	1	1716–1865	1717	10	24		0.4
	81	24.2	2	1716–1909	1720	8	27	1.42	0.2
FV	39	13.4	1	1750–1870	1759	9	16		0.4
FL	40	13.4	2	1764–1910	1777	11	7	0.80	1.0
	62	19.4	1	1765–1900	1672	7	12		0.5
	90	27.3	2	1765–1900	1776	5	12		1.0
PV	47	14.4	2	1755–1826	1759	5	28	1.44	0.2
DL	4	6.5	1	1765–1920	1767	24	9		0.4
	37	12.7	2	1765–1916	1769	12	11		0.5
CH	3	6.4	2	1757–1852	1761	15	20	1.85	0.5
	55	18.1	1	1723–1921	1730	11	14		0.4
CP	12	8.1	1	1596–1757	1602	20	4		0.2
SB	79	24.0	2	1819–1915	1826	4	28		0.4
BO	36	12.6	1	1711–1924	1712	17	14		0.4
	70	21.1	1	1660–1891	1669	11	26		0.2
	101	42.0	1	1660–1911	1670	6	42	1.45	0.2
BI	23	10.1	1	1657–1797	1661	14	7		0.5
	32	11.7	2	1776–1915	1780	12	8	1.27	1.0
	43	13.5	1	1653–1814	1657	12	10		0.4
W	53	17.3	2	1753–1925	1768	10	10		0.2
	94	34.3	1	1753–1925	1770	5	20		0.1
EP	7	7.7	2	1827–1918	1831	12	10		0.5
	31	11.6	1	1785–1912	1792	11	14	1.50	0.5
	41	13.4	2	1755–1915	1762	12	14	1.66	0.5
	85	26.8	1	1755–1915	1775	6	20		0.4
BC	25	10.3	1	1735–1878	1738	14	5		0.5
	33	11.7	2	1788–1916	1790	11	9		0.4
	69	20.6	2	1755–1919	1769	8	10		0.4
CVP	8	7.7	2	1813–1920	1816	14	8		0.4
	66	20.3	1	1750–1922	1751	8½	12		0.4
OC	27	10.6	2	1717–1886	1720	16	7		0.4
	34	11.7	1	1732–1907	1739	15	5		0.4
	48	14.4	2	1768–1911	1775	10	7		0.4
	71	21.1	1	1710–1910	1711	9½	7		0.4
	76	23.2	1	1710–1895	1716	8	8		0.4

Weak Cycles

Curve	Number	Cycle	Duration	First max.	Rows	P. ct. Amp.	A. D. ratio	Vertical scale
BMH	105	7.6	1758–1894	1763	18	5	1.32	1.0
	107	10.1	1638–1859	1641	22	7	1.22	1.0
	111	11.9	1618–1891	1628	23	3		1.0
	116	17.3	1744–1916	1747	10	14		0.4
	117	18.0	1630–1737	1635	6	16	1.29	0.2
	122	23.9	1622–1884	1628	11	16	1.48	0.4
AE	102	5.9	1723–1911	1728	32	5	1.29	0.5
	118 or	18.2	1720–1919	1726	11	12		0.5
	119 or	19.5	1723–1917	1732	10	11	0.85	0.4
	121	23.4	1723–1909	1723	8	30		0.4

42 Western Groups—Concluded

Weak Cycles—*Continued*

Curve	Number	Cycle	Duration	First max.	Rows	P. ct. Amp.	A. D. ratio	Vertical scale
C	108	10.2	1790–1911	1796	12	7	1.35	0.5
	110	11.2	1780–1913	1781	12	11	1.28	0.4
	115	15.3	1780–1917	1782	9	10	1.35	0.4
	120	19.5	1795–1911	1796	6	17		0.4
HNT	106	9.3	1760–1917	1765	17	4	0.92	0.5
	109	11.1	1760–1914	1760	14	7	1.01	1.0
	113	13.4	1760–1920	1761	12	4	0.84	1.0
	114	14.7	1759–1920	1771	11	12	1.31	0.5
Y	103	6.2	1700–1761	1703	10	6		0.5
	104	6.5	1787–1916	1790	20	3	0.88	1.0
	112	12.7	1700–1915	1703	17	5	1.15	1.0

Preferred Cycles (Supplementary Group)

Curve	Number	Cycle	Under-lines	Duration	First Max.	Rows	P. ct. Amp.	Vertical Scale
LW	129	8.2	2	1754–1917	1761	20	12	0.4
ST	141	17.2	1	1749–1920	1757	10	07	0.5
BDF	147	20.4	1	1782–1913	1793	6½	19	0.4
SR	139	14.4	2	1749–1921	1754	12	13	0.5
SC	143	17.4	1	1747–1920	1757	10	13	0.5
PNL	128	7.6	1	1760–1919	1763	21	09	0.5
RH	146	19.9	2	1750–1918	1767	8½	13	0.5
FLH	125	6.9	1	1750–1921	1757	25	02	0.5
	142	17.3	2	1750–1922	1754	10	09	0.4
GC	149	20.8	1	1750–1915	1765	8	27	0.4
FV	148	20.5	1	1750–1913	1766	8	23	0.4
	161	35.0	2	1746–1920	1767	5	26	0.2
FL	126	6.9	2	1750–1908	1757	23	05	1.0
PV	159	32.0	1	1750–1909	1761	5	27	0.2
DL	127	7.2	1	1765–1922	1765	22	03	1.0
	138	14.2	2	1765–1920	1772	11	14	0.4
	140	16.4	1	1765–1920	1766	10	17	0.5
KF	156	24.2	1	1792–1912	1813	5	22	0.5
	158	31.2	1	1792–1916	1800	4	21	0.4
CP	157	28.6	2	1750–1921	1755	6	16	0.2
SB	154	23.0	1	1819–1910	1829	4	28	0.4
	133	9.8	1	1819–1921	1826	10½	10	0.5
BO	136	11.3	1	1750–1918	1757	15	03	0.5
W	134	10.4	1	1749–1925	1749	17	04	0.4
	152	22.5	1	1746–1925	1748	8	12	0.1
BC	151	21.7	2	1746–1919	1747	8	19	0.2
CVP	123	6.8	1	1750–1919	1751	25	04	1.0
	150	21.2	1	1750–1919	1751	8	13	0.4
OC	153	22.6	1	1750–1907	1751	7	05	0.4
BMH	162	35.0	1	1745–1919	1767	5	23	0.4
AE	155	24.0	2	1750–1917	1768	7	23	0.4
C	132	9.3	1	1778–1916	1784	15	08	0.5
	145	18.8	1	1778–1918	1793	7½	15	0.5
HNT	124	6.8	1	1750–1919	1752	25	05	1.0
	130	8.6	1	1749–1920	1751	20	04	0.5
	160	34.5	1	1749–1920	1769	5	24	0.4
LNT	135	11.1	1	1750–1915	1760	15	06	1.0
BES	131	8.9	1	1775–1916	1783	16	07	0.5
	137	14.1	1	1775–1915	1787	10	08	0.5
SF	144	18.4	1	1750–1915	1761	9	11	0.4

preliminary results, subject to improvement but certainly showing at this time some of the general facts. The summary in a frequency periodogram, fig. 55, contains a significant generalization from these data.

Evaluation of Cycles in the 42 Groups—The preceding lists contain the results of analyses by Mr. Schulman of the 42 Western groups with special attention given to the dates of beginning and ending of cycles. About 100 cycles which he had "underlined" form perhaps the basis of the list; underlining means[1] that they showed signs of special strength; approximately 175 apparently weak cycles in addition to those listed are here omitted. But he has included some 40 cycles observed by the writer and reported in Volume II (1928, Chapter VII). They have been observed by Mr. Schulman but were not underlined. They are, he says, equivalent to a preferred set of values without underline.

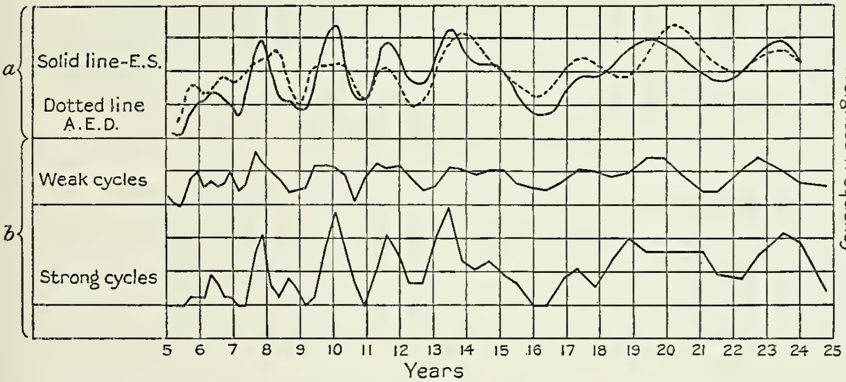

FIG. 41—Frequency periodograms of 42 Groups:
(a) obtained by two independent observers.
(b) weak and strong cycles compared (as recorded by Schulman).

The amplitudes listed were determined by the usual arithmetical summation process described in a previous chapter. By actual tests it was found that amplitudes are not changed to any appreciable extent in that summation by letting some rows run one unit beyond the other rows, as is necessary in testing fractional periods (periods that are not integers: See Chapter II). After plotting the summated curve, the amplitudes were measured on the plots and the value quoted is essentially half the range from the lowest to the highest point of the plotted and smoothed curve. The difficulty was encountered that the curves were not always of simple and regular type. Often there were secondary crests that are non-symmetrical so that the curve can not be classed as a multiple. That is quite characteristic of natural sequences.

These summations have formed the basis of a study by Mr. Schulman of the meaning of underlines in terms of certain statistical quantities. He finds that when the underlining is compared with the amplitude and the A.D. ratio, both the percentage amplitude and the A.D. ratio increase with the stronger emphasis of each additional underline. In every class, however, there is a large amount of scatter about the mean relations between these three quantities. The source of the scatter lies in two factors: First, each of the four or five underline classes covers a considerable variation in emphasis and hence each estimate of underlines has a personal element. Second, many cycles which were quite strong in the cyclogram yield on summation small amplitudes and A.D. ratios due to interfering cycles; in other words the form of the cycle, the relation of the interfering cycles, and the brevity of the data, have not permitted the satisfactory cancellation of the interfering effects on which the summation process is based. It is evident that the cycle underlining is perhaps fully as important as the percentage amplitude or the A.D. ratio.

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[1] See also pages 146 and 147.

There is evident within each emphasis class a systematic decrease in percentage amplitude with increase in the number of rows; this arises partly because the number of cycle repetitions is one of the factors considered in assigning underlines.

The preceding discussion is based on the following tables:

Cycle emphasis class	Frequency	Ave. No. of Rows	Mean Amp., p. ct.[1]	Ave. Dev. of Amp., p. ct.[1]	Mean Amp. / Ave. Dev.	Ave. Duration Yrs.
2 underlines, ES	36	9.8	18.6	±8.6	2.16	151
1 underline, ES	66	11.6	13.9	±6.8	2.05	165
No underlines, ES	19	12.6	10.4	±4.8	2.16	169 (for 195 cycles)
Addit. underl., AED	41	11.5	13.2	±6.4	2.06	

Cycle emphasis class	Frequency[2]	Ave. A. D. ratio	Stand. Dev.	A. D. Ratio / Stand. Dev.	Mean Amp., p. ct.[1]
2 underlines, ES	15	1.43	±.23	6.2	20.3
1 underline, ES	17	1.30	±.29	4.5	13.2
No underlines, ES	13	1.18	±.20	5.9	8.8

[1] Percentage refers to mean ring thickness.

[2] This table includes only cases in which the A. D. ratio had been computed.

RECORDS OF PAST CLIMATES

The preceding lists have contained the analyses of many tree-ring records that originated in modern times, chiefly since 1750. Those records came from thousands of square miles of area and showed similarity in the general characters of climatic change for that region. Now we deal with the cognate idea of extension in time. Appropriate questions at once occur to us: If two areas have agreed for the last 150 years, did they agree for the last 1500 years or more? If the discontinuous periods in climate show resemblance to the sun in the last hundred years while the sunspot cycle was stable, did they show resemblance during the preceding hundred years when the sunspot cycle was unstable? Can we infer a length of the sunspot cycle and dates of maxima or minima from tree records extending back 1900 years in Arizona and 3200 years in California, the California records though longer having a less well-established relation to rainfall? And, more important than the other questions perhaps, can we find evidence of recurrence of the same cycle; is there some plan on which it comes back; and can we infer any probability of its return at a definite time? Such knowledge would compensate for some of the difficulties introduced by the temporary character of climatic cycles. What of the cycles in the much more distant past? Good tree records are available from tertiary sources, say 50,000,000 years ago, perhaps very much more, and sediments carry us to much more distant ages. Do we get any hints from these sources regarding the stability or instability of our sun?

We have at this time two types of records of past climates: namely, accurately dated records in Arizona and California, abundantly cross-identified in great numbers of trees, and, second, undated geological records in fossil trees largely without cross-identification, and in sediments with cross-identification, in all of which cycles may be studied.

SEQUOIA CHRONOLOGY AND CYCLE RECURRENCE

The difficulty with the study of cycles in climate has been the limited lifetime or duration of any one cycle. The favorable possibility of finding a definite recurrence of cycles has been recognized since 1927, and the great sequoias have seemed the most promising location for the search. We have in our laboratory 50 radials of these trees, of which about half show 2000 rings or more, and four extend back 3100 years; one reaches to 1305 B.C. They fall into two groups, the Grant Park sequoias and the Springville sequoias, some 40 miles apart. It was discovered about 1921 that the double sunspot cycle of 22 or 23 years is more common in these trees than the 11-year cycle. The pine tree curve of the Sierra Nevadas resembles the sequoias in giving prominence to a cycle of about 23 years. A correlation periodogram of this series of data by Dr. Alter, reproduced in figure 53, shows a pronounced crest at about 22½ years and its multiples, thus confirming these results.

In 1927 a study was made of several different sequoia groups in which the presence of the solar influence had been suspected. Trials of a 23-year cycle give us a series of curves each 23 years long, that are consecutive and continuous through nearly 3000 years and each curve is a running or overlapping mean of three successive 23-year intervals.

A large percentage of these 130 curves show clearly a 23-year cycle or some subdivision of it up to five equal parts. The division into 4 parts is illustrated in figure 42. Of course, this work is far from finished, but these results apparently agree in the two separated sequoia groves. Limited checking has also been carried successfully to other sequoia groupings that for various reasons have been segregated. As a matter of safety a couple of hundred years of sequoia values were "scrambled" and then treated by the same integration method, as shown in figure 43. So we learned that the manner of smoothing eliminates two-year cycles which in turn leaves three-year cycles or eight crests in the curve most numerous (theoretically), seven crests next and so on. One scrambled curve has five crests, and one has four, showing that some of the fractionizing in the real curve may be accidental, especially in isolated cases. In the scrambled curves the same fraction does not occur twice in succession; but in the natural curves the same

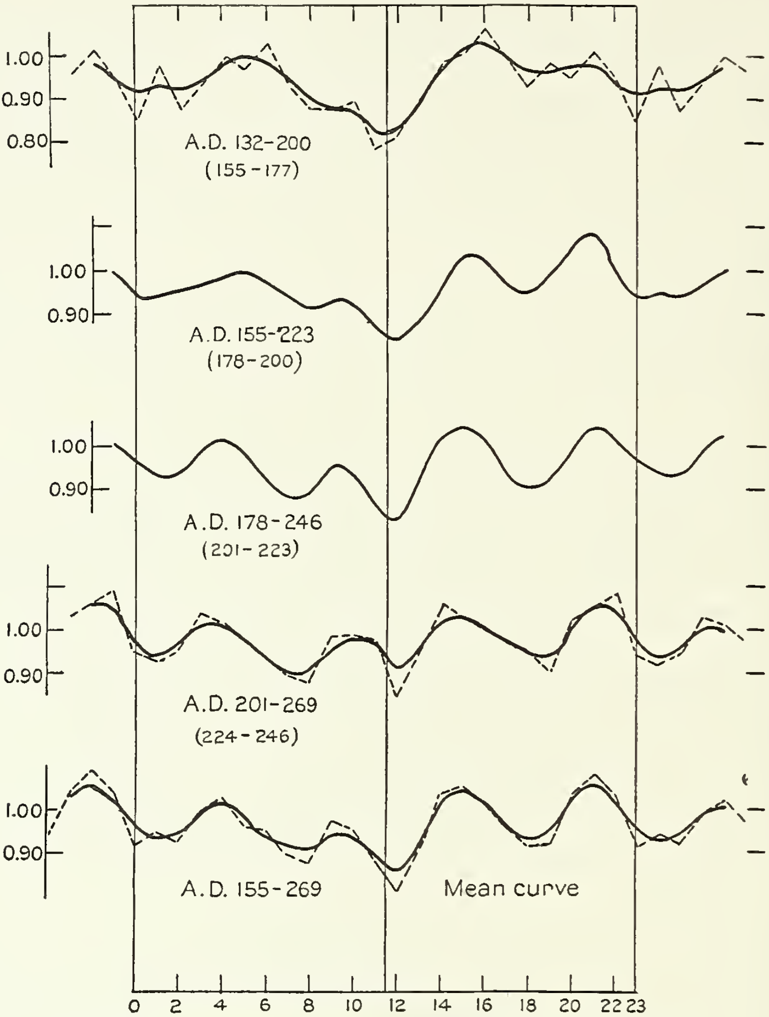

Fig. 42—Hellmann cycle in sequoias, A.D. 155 to 246, using "triple lag" method. Note: dotted lines represent the original unsmoothed means.

occurs three to five or more times in succession and the cycles seem to merge as they change and the chances are greatly against accident. As the length of the fraction increases, for example, from 4½ to 7½ years, accident becomes less and less likely. So even three curves in succession showing three subdivisions are very probably real. We find, for example, a Hellmann cycle lasting from about 1760 to 1910 or so, an interval of 150 years containing more than 25 repetitions, as appears in figure 44. It does not disappear during the changes in the sunspot cycle near 1800.

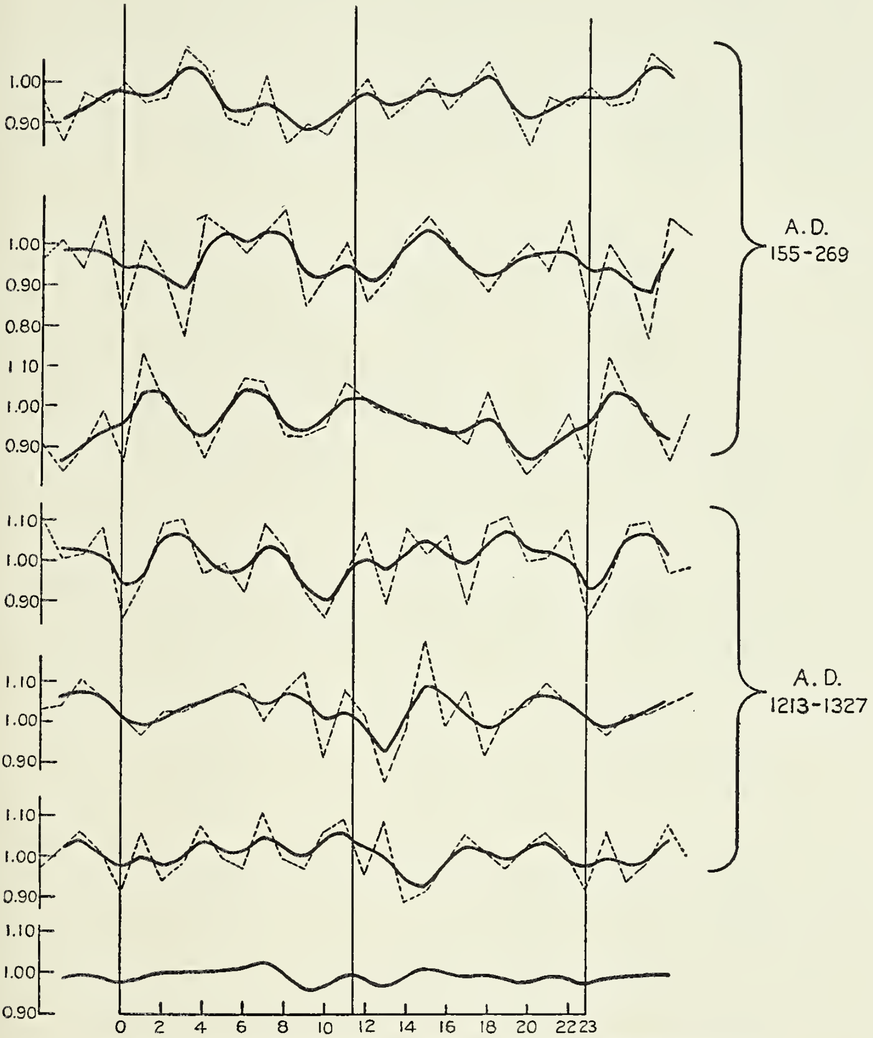

FIG. 43—Scrambled sequoia values tested by "triple lag" method.

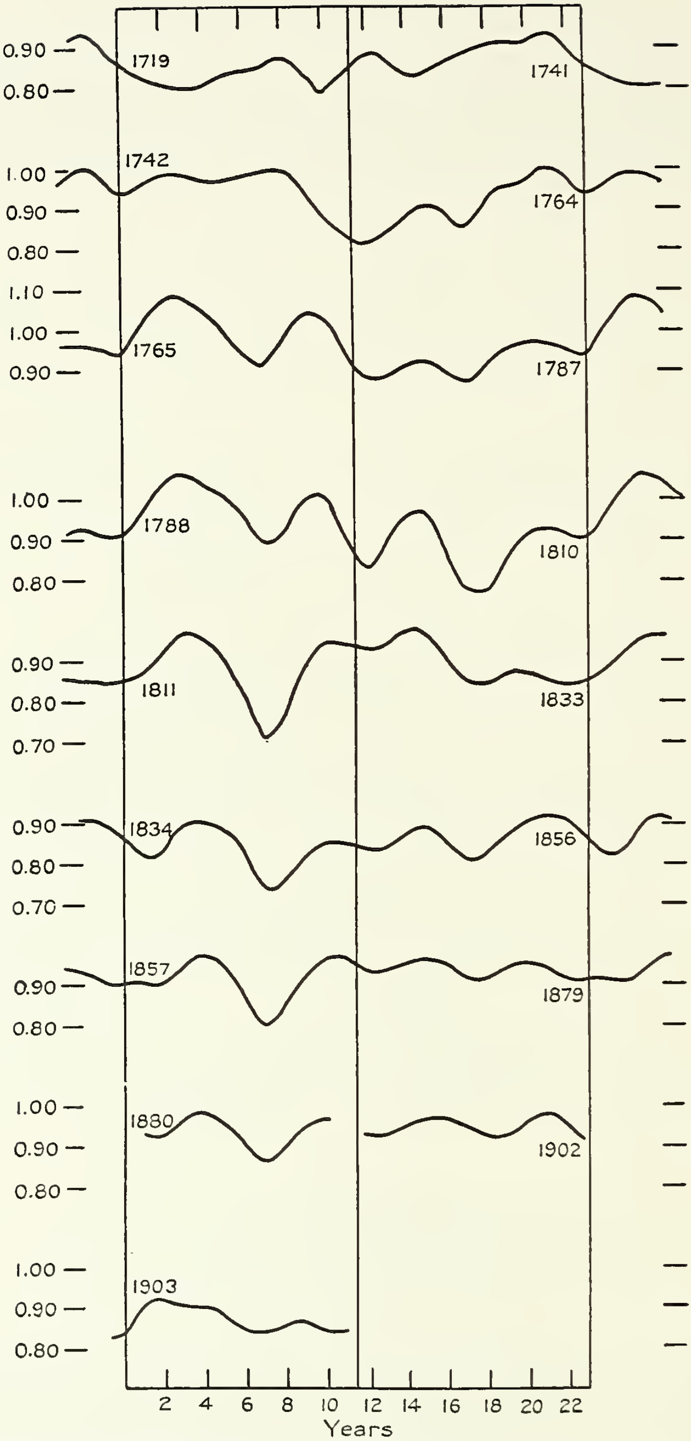

FIG. 44—Hellmann cycle in recent sequoia records. Running means of three successive cycles of 23 years ("triple lag" method, incomplete after 1891).

In these 130 curves, covering the age of the sequoias, a recurrence cycle of about 270 years seems to be a common character, as shown in this preliminary study. A cycle about 100 years long is common to them all and something near 220 years is seen occasionally. Ordinary cycles of all these values are mentioned by Turner. Something near 300 years is discussed by Clough. Dr. Alter mentions 250 years for possible recurrence. The double value near 560 years probably exists in our data, and it is possible that it will prove important. In order to visualize the possibilities, a 275-year length is taken as a workable solution for the time being. A provisional pattern based on this 275-year recurrence is shown in figure 45. This diagram shows the sequence of different short cycles in the 275-year pattern derived from 2000 years of the Grant Park sequoias and is a very promising sign at the present time. In it we find that the persistence of the Hellmann cycle since 1750 agrees with previous recurrences of that cycle. If the various cycles continue as they have done, we have some reason to expect that through the next 70 years this Hellmann relation should be less conspicuous or absent, with a probability of replacement by a 23-year cycle or the same divided into five equal parts.

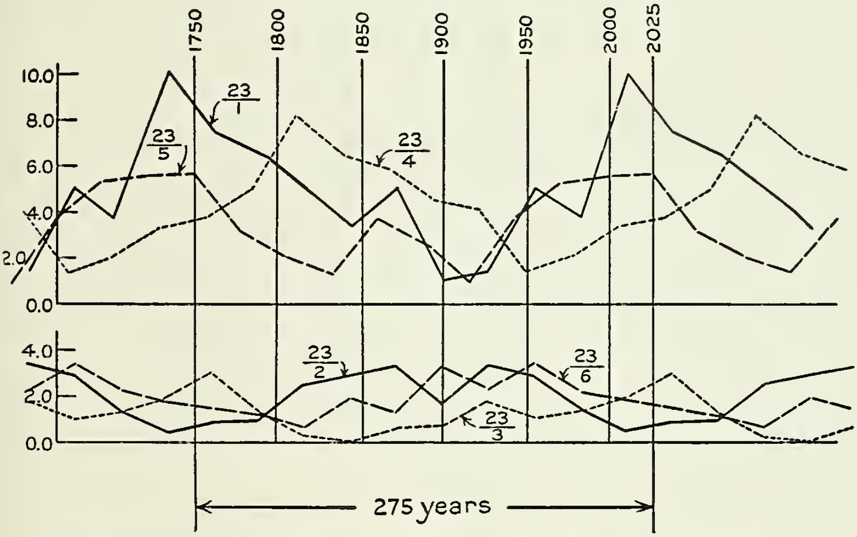

FIG. 45—Average cycle recurrence in Grant Park sequoias in 2100 years.

This pattern therefore encourages us to hope that from the giant sequoias, checked by historical material, we shall obtain in some form of cycle sequence a real step forward toward a theory of climatic change and long-range prediction. This is the thought that inspires our attack upon the cycles in the long chronologies.

Sequoia Chronology[1] *Cycles*

Cycle, yrs.	Number	Underl.	Duration	First Max.	Rows	P. ct. Amp.	AD Ratio
4.9	163	2	1188–1241	1190	11	6	
5.0	164	1	370–499	370	26	3	
5.2	165	1	018–059	019	8	4	
5.2	166	no	782–869	785	17	3	1.44
5.2	167	no	1812–1910	1816	19	2	0.98
5.6	168	no	215–298	217	15	3	
5.7	169	no	1777–1913	1781	24	4	1.84
6.2	170	1	1295–1412	1300	19	4	2.08
6.2	171	1	1468–1566	1471	16	5	2.28
6.2	172	no	1755–1810	1755	9	8	2.22
6.3	173	no	376–501	376	20	2	
6.5	174	no	585–850	590	41	2	1.08
6.6	175	1	000–118	000	18	2	
6.6	176	2	226–291	227	10	3	
6.7	177	1	1070–1156	1076	13	5	1.32
6.7	178	1	1157–1263	1160	16	3	1.14
6.9	179	1	293–368	296	11	6	1.48
7.0	180	1	000–146	003	21	2	
7.1	181	no	798–889	800	13	4	
7.3	182	no	1650–1773	1651	17	3	1.20
7.5	183	1	450–606	454	21	3	
7.6	184	1	1010–1123	1011	15	4	1.80
7.7	185	1	000–114	004	15	4	1.17
7.7	186	1	1250–1349	1252	13	4	1.24
8.1	187	no	690–762	693	9	7	1.77
8.2	188	no	955–1093	960	17	4	1.04
8.6	189	1	360–445	367	10	9	1.63
8.7	190	1	226–295	234	8	4	
8.9	191	x	1315–1403	1319	10	5	1.27
9.2	192	1	033–207	037	19	6	1.82
9.2	193	no	630–684	635	6	10	1.69
9.7	194	no	877–983	882	11	5	
9.7	195	1	1730–1807	1732	8	8	1.49
9.9	196	1	1140–1238	1141	10	6	1.24
10.5	197	1	765–1121	770	34	3	
10.5	198	1	1650–1733	1653	8	4	1.06
10.5	199	1	1812–1905	1816	9	5	1.50
10.7	200	no	800–895	806	9	6	
10.7	201	no	896–1120	906	21	3	
11.2	202	1	677–844	681	15	6	1.43
11.2	203	no	350–517	360	15	2	
11.2	204	no	518–674	526	14	5	
11.4	205	2	1777–1913	1780	12	7	1.60
11.5	206	no	87–235	090	13	9	
11.8	207	2	1238–1343	1247	9	11	1.81
12.1	208	1	1300–1420	1307	10	5	1.05
12.1	209	2	1457–1565	1465	9	5	1.09
12.1	210	2	1590–1650	1592	5	6	1.25
12.6	211	1	360–498	369	11	6	1.26
13.1	212	1	000–222	009	17	5	
13.1	213	2	363–768	365	31	5	1.73
13.3	214	1	1722–1907	1733	14	7	1.29
13.6	215	no	220–355	233	10	6	
14.4	216	no	1650–1750	1651	7	6	1.34
14.6	217	1	043–173	045	9	10	1.25
15.0	218	no	345–449	351	7	5	
15.1	219	no	1200–1305	1214	7	10	1.24
15.2	220	no	000–242	006	16	4	
15.3	221	no	1647–1799	1648	10	6	
15.7	222	no	800–893	807	6	6	
15.9	223	no	1250–1424	1258	11	5	1.28

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[1] For column titles, see p. 154. Percentage amplitude is in terms of mean ring thickness. Vertical scale is normal for all summation curves, that is, 10 per cent per division.

Sequoia Chronology Cycles—Concluded

Cycle, yrs.	Number	Underl.	Duration	First Max.	Rows	P. ct. Amp.	AD Ratio
15.9	224	1	1794–1904	1799	7	8	1.57
16.4	225	1	900–1194	903	18	7	1.51
17.0	226	1	1500–1907	1509	24	5	1.11
18.3	227	x	1300–1738	1313	24	4	
19.2	228	no	000–210	002	11	6	
19.4	229	no	350–853	363	26	3	
20.3	230	no	1400–1906	1401	25	5	
22.1	231	no	800–1296	814	22½	5	
22.3	232	no	1250–1740	1260	22	4	
23.0	233	no	1740–1900	1745	7	10	1.27
23.2	234	no	700–977	710	12	5	

The author's analysis of the sequoia chronology was largely done in 1918; this was reviewed more recently at various times. Mr. Schulman did this work on these data in the last year; the tabular matter here given is based on Mr. Schulman's results, checked by the author's. Amplitudes have been worked out under the direction of Dr. W. S. Glock, Mr. Edmund Schulman, and Mr. G. C. Baldwin.

CENTRAL PUEBLO CHRONOLOGY

The sequoia chronology just described is taken from continuous tree records of extraordinary length: four of the trees show more than thirty centuries and large numbers reach 2000 years. In sharp contrast, the Arizona chronology is built of a large number of overlapping records matched together by cross-dating of ring groups. It would perhaps be difficult to find another locality where this could be done. It was accomplished by the interest and generous aid of the archæologists. A partial account is given elsewhere.[1]

Besides the National Geographic Society, other institutions and persons gave important help: the American Museum of Natural History in New York City, the Museum of Northern Arizona, Dr. and Mrs. Colton at Flagstaff, the University of Arizona, the Carnegie Institution of Washington and many interested students and friends. The archæological phase started in 1914 and in 1929 passed a milestone in the closing of a "gap" between dated records extending back to or a little before 1300 and a "floating" chronology extending back to what later proved to be A.D. 700. This gave to the climatologist a bio-climatic record back to that time. The extension back to A.D. 11 and the needed strengthening in the early Eighth Century came very largely from the splendid collections of Mr. Earl H. Morris between 1927 and 1933.[2]

Definite work on the portion of this chronology before 700 began in May 1931 and its accuracy was considered assured by the late summer of 1934. Yet certain confirmations in Flagstaff specimens examined in February 1935

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[1] *Dating Pueblo Bonito and Other Ruins of the Southwest,* Technical Monograph published by the National Geographic Society; Paper Number 1 in the Pueblo Bonito Series. See also the earlier account: *The Secret of the Southwest Solved by Talkative Tree Rings*, Nat. Geog. Mag., Dec. 1929.

[2] The valuable collection work of Mr. Morris was aided by the Carnegie Institution of Washington, the American Museum of New York, the University of Colorado, Mr. C. L. Bernheimer and others. A specially valuable specimen was collected by Dr. Florence M. Hawley while giving field instruction in connection with the Department of Archæology of the University of New Mexico. Other aid is mentioned on pages 6–7.

Central Pueblo Chronology

Cycle, yrs.	No.	Underl.	Duration	First Max.	Rows	P. ct. Amp.	A. D. Ratio	Vertical Scale[1]
5.2	235	2	1500–1665	1504	32	9	1.87	
5.7	236	no	1750–1926	1753	31	3	1.17	
5.9	237	no	088–211	093	21	5	1.31	
6.1	238	no	1100–1270	1105	28	6		
6.2	239	no	695–768	697	12	13		
6.5	240	1	1500–1746	1505	38	8		
6.7	241	1	60–247	066	28	8		
6.7	242	x	370–503	375	20	4		
6.8	243	1	573–660	575	13	22		
7.0	244	no	1450–1498	1455	7	13		0.5
7.0	245	1	200–339	206	20	15		0.5
7.0	246	no	340–451	345	16	8		
7.3	247	1	890–977	891	12	9	1.13	
7.6	248	1	1450–1647	1453	26	11		
8.0	249	no	242–401	246	20	10		
8.1	250	1	1060–1197	1066	17	9		
8.7	251	no	400–616	408	25	11		
9.3	252	no	100–211	105	12	6	0.97	
9.4	253	1	1194–1259	1201	7	20	1.68	
9.7	254	1	829–1041	833	22	12		
9.7	255	no	1101–1197	1107	10	10		0.5
10.4	256	no	080–204	083	12	7	1.15	0.5
10.4	257	1	1300–1413	1301	11	12		0.5
10.4	258	no	1415–1497	1416	8	8		
10.4	259	1	1500–1697	1505	19	11	1.53	
11.4	260	1	1748–1929	1749	16	11	1.49	0.5
11.5	261	1	1463–1646	1468	16	12	1.38	
11.8	262	no	060–248	064	16	9	1.08	
11.9	263	no	270–543	272	23	8		
11.9	264	no	700–901	708	17	10		0.5
11.9	265	1	1020–1197	1029	15	14		0.5
12.1	266	2	1310–1563	1320	21	14	1.92	0.5
12.3	267	1	170–329	170	13	15		0.5
12.8	268	1	950–1205	950	20	12		
13.0	269	1	1500–1772	1512	21	10	1.47	
13.5	270	2	90–237	098	11	13	1.41	0.5
13.5	271	no	238–494	250	19	10		0.5
13.6	272	2	1807–1928	1812	9	13	1.11	
13.7	273	no	1300–1641	1305	25	10	1.33	
14.3	274	1	400–685	408	20	12	1.28	
15.4	275	no	1130–1298	1133	11	13		
15.7	276	2	10–339	017	21	17	1.93	
15.7	277	2	350–443	358	6	20	1.13	
16.5	278	2	150–347	152	12	22	1.91	0.5
16.5	279	1	1691–1822	1694	8	14		
17.0	280	x	700–1192	703	29	3		
17.1	281	no	10–505	014	29	14	(instead of 15.7 and 16.5)	
17.3	282	no	1300–1645	1305	20	7		
17.8	283	x	1500–1766	1514	15	11		
19.0	284	no	1176–1498	1185	17	8		
19.2	285	2	840–1165	854	17	15	1.47	
19.5	286	no	1500–1772	1512	14	10		
19.5	287	2	1770–1925	1772	8	17		0.5
19.5	288	no	010–496	027	25	8	0.95	
20.0	289	x	400–649	402	12½	10		0.5
22.5	290	2	400–691	420	13	14		
22.5	291	no	1520–1666	1530	6½	15		
23.0	292	2	1734–1929	1747	8½	18		
23.2	293	1	700–989	712	12½	15	1.25	0.5

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[1] Vertical scale of summation curves in appendix is 1.0 unless otherwise indicated.

Central Pueblo Chronology—Concluded

LONG CYCLES									
$\left[\frac{\text{Cycle}}{5}\right]$	Cycle, yrs.	No.	Underl.	Duration	First Max.	Rows	P. ct. Amp.	A. D. Ratio	Verticle Scale
7.4 and	37.0	294	2	1100–1319	1125	6	18	1.67	
7.5 or	37.5	295	1	1595–1929	1610	9	10	1.75	
7.5	37.5	296	2	1080–1924	1085	22½	8	1.98	
10.0	50.0	297	1	1530–1929	1560	8	11	1.45	0.5
10.5	52.5	298	1	1250–1534	1270	5½	19	1.48	0.5
11.0	55.0	299	1	065–669	110	11	10	1.07	
11.1	55.5	300	2	640–1139	675	9	16	1.63	
11.7	58.5	301	1	705–1929	725	21	9	1.54	
13.2	66.0	302	1	125–554	150	6½	14	1.44	
14.7	73.5	303	1	555–1914	585	18½	11	1.45	0.5
19.2	96.0	304	2	010–679	015	7	15	1.40	
19.6	98.0	305	2	710–1929	780	12½	13	1.36	
23.5	117.5	306	2	700–1929	730	10½	13		
26.0	130.0	307	1	120–639	150	4	13		

were very gladly recognized. It should perhaps be repeated that the value was realized of this continuous ring sequence 1900 years long in a dry region where the trees were giving approximate rainfall records. It also seemed to the writer that it more than doubled the value of the sequoia chronology because it supplied a second sequence for comparison purposes. It also lays a foundation for estimates of yearly rainfall values in prehistoric times. It should be added that this chronology is not yet in completely final form. Improvement is coming through a better understanding of the climatic characters in the growth rings. It is not probable that any important changes will be required.

Mr. Schulman is quoted in the following report on cycle comparisons between Arizona and California chronologies:

> "Simultaneous analysis of the two long chronologies shows some striking points of agreement in the cycle patterns, in spite of the difference of some 600 miles in the source areas of the respective specimens. At many settings the patterns show such fine resemblance in the details as to leave the strong impression that the same forces causing fluctuations are operating in both regions. However, emphasis on different cycles is visibly different in many cases in the two regions, hence there is no perfect correspondence in the concurrent maxima. Agreement is seen in the entire 1900 years; there is a strong suggestion that it is successively better in more recent times.
>
> "In the settings showing some of the best points of correspondence, given below, there is usually not only agreement in the particular cycle setting, but also in other cycles evidenced by slant alignments in the cyclogram. The following analyses made in five overlapping intervals show cycles common to the two chronologies; the cycle lengths listed are of course in years.
>
> 1500 to 1900: 10, 11½ (1750–1900), 13.5 (1750–1900), 17, 19
> 1100 to 1600: 10 (1100–1250), 12 (1300–1600), 15 (1100–1300), 19–20, 27
> 700 to 1200: 13½ (700–850), 16½ (950–1200), 19, 23 (700–1000)
> 450 to 900 : 7, 13 or 14, 27
> 10 to 500 : 7, 13 or 14
>
> "Simultaneous analysis of the compressed curves of the two chronologies (5 year means), viewing 1900 years at once, yields even better results. The following cycles were found to agree well.

Years	
37.5	(1000–1914); fainter in sequoias
58	very good in both
66	(first 1000 years); fair but not as important as the others.
95–98	excellent agreement throughout.
117	the half-cycle, 57 ± years is frequently seen; emphasis sometimes changes from fundamental to intermediate crests, not always similarly in the two regions.

"In every cycle almost all corresponding maxima may be recognized, although there is much variation in maxima strength. There are indications of a long cycle of somewhat less than three hundred years which seems to form, with the last two above, a controlling group."

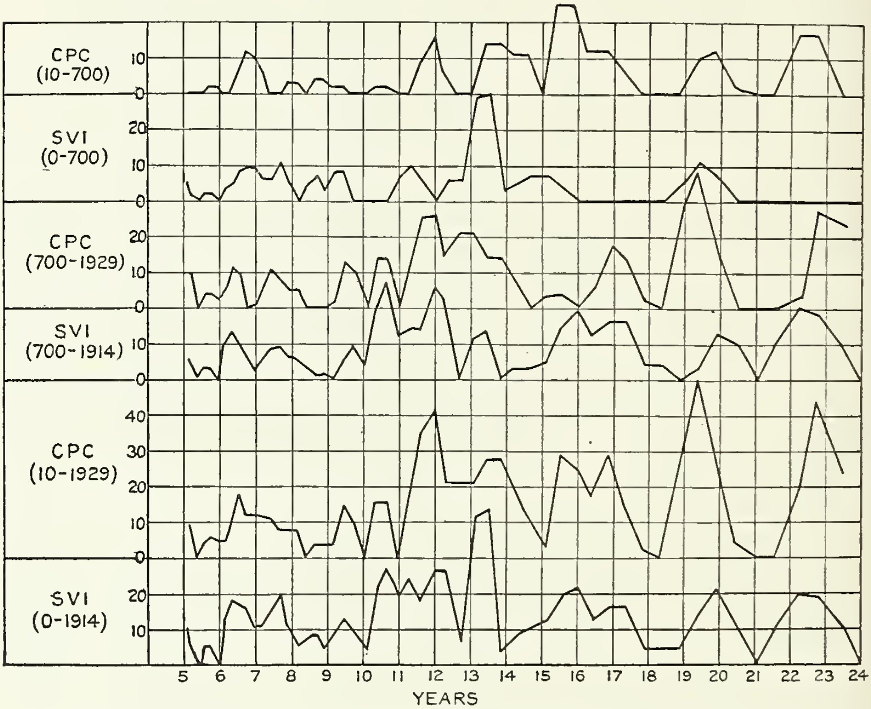

FIG. 46—Frequency periodograms of Central Pueblo Chronology (CPC) and Sequoia Chronology (SVI).

GEOLOGICAL MATERIAL FOR CYCLE ANALYSIS

Its Character—Many collections of fossil wood have been examined but nearly always the specimens are massive pieces, and the long, unbroken sequences of rings for which we are searching are quite absent. That is not surprising, for the breakage of such wood is not normally radial, as we would wish, nor have long sequences been specially sought. In fact the deliberate collection of long sequences in the field is very difficult. Unaltered wood such as the "buried trees" near Flagstaff or the large logs in the German peat beds is far more likely to show desired records.

Cycle, yrs.	Underl.*	Duration, yrs.
#1: 151 yrs.		
5.1	no	52
6.0	no	151
8.0	1	151
9.5 or	x	151
10.1	no	151
10.9	x	151
12.1 (oc ½)	1	151
13.8	no	151
16.0 (½)	1	119
24.0±	no	151
#2: 141 yrs.		
5.1	x	141
6.0	x	141
8.0	x	141
9.5	1	141
10.1	x	141
10.9	x	141
12.1 (oc ½)	no	141
13.8	no	141
18.7 (oc ½)	no	141
#1 and 2: 153 yrs.		
5.3	no	153
5.9	no	30
6.6	x	114
8.3	1	109
12.2	1	153
16.0 or	no	153
17.2 (oc ½)	1	153
24.2 (oc ⅓)	1	153
#3: 69 yrs.		
6.0	no	69
7.4	no	69
9.4	2	69
12.1	1	52
14.6 (oc ½)	x	69
19.2 (½)	no	69
#7: 181 yrs.		
5.5	no	181
8.3	x	181
9.8	no	111
11.0 (oc ½)	x	181
14.0	2	181
17.0	1	181
23.9	x	181
27.8 (½)	no	181
#8: 94 yrs.		
5.2	no	94
6.5	x	94
8.7	no	77
10.4 (oc ½)	1	94
12.1	2	94
17.9	x	94

Cycle, yrs.	Underl.	Duration, yrs.
#9: 80 yrs.		
7.5	no	80
8.5 (oc ½)	no	80
9.9	1	80
11.7	1	80
14.6	no	80
20.8	no	80
24.0±	no	80
#10: 93 yrs.		
5.6 (oc ½)	no	93
7.9	no	93
8.4	no	93
10.1	x	70
11.7	1	93
14.0	2	93
20.8	no	93
24.0± (oc ½)	no	93
#11: 157 yrs.		
8.9	x	157
11.1	no	157
12.2	2	157
13.9	x	157
17.9	x	157
22.0	x	157
#13: 181 yrs.		
6.9 (oc x 2)	no	131
9.3	1	141
12.3	2	121
14.3	x	181
19.2	1	181
#14: 174 yrs.		
5.2	1	109
7.1	x	174
10.6 (oc ½)	no	174
11.8	no	174
14.5	2	174
15.8	no	101
17.5 (oc ½)	no	171
#15: 98 yrs.		
5.2	x	98
6.0	no	98
7.1	x	98
10.2 (oc ½)	1	98
11.8	no	98
14.6	1	98
17.5	1	98
20.6 (oc ½)	no	98

* For underlines, etc., see pages 146 and 147.

The varves of De Geer and Antevs provide continuous sequences that cover thousands of years. The Permian anhydrites of Udden do the same to a less degree. This anhydrite even with errors up to 2 per cent shows some 1400 years of practical continuity. The longest continuous sequences found by Bradley in the Green River formation of southern Wyoming are less than 100 years. I have no doubt that we have barely touched the valuable material along these lines that will eventually be available.

Since the geological material is without actual dating and is not cross-identified, the common way of presenting results from it is in the frequency periodogram; that is, a plot of the frequency of occurrence of cycles of different lengths. Such periodograms may be seen in figure 55, where results from widely different sources are compared.

BURIED TREES

At Flagstaff, Arizona, in 1904, the writer discovered in an arroyo a tree stump in place buried 16 feet deep in the valley fill. In 1919 and for several years after, with the aid of Dr. E. S. Miller and Major L. F. Brady, a large number of tree sections were secured in the same arroyo from different depths between 1½ feet and 16 feet. The annual rings in the logs at shallow depth were of the sort now growing in the pines thereabouts—dry climate rings. The rings at 12 and 16 feet in depth were wet climate rings—large and showing a slow surge in size characteristic of a relatively continuous water supply. This contrast occurring in one locality appeared to indicate a climatic change. Ten of these buried trees, chiefly from the upper levels, gave excellent measured records aggregating more than 1400 years.

These records have been analyzed by the writer from time to time, with the result of finding cycle lengths at 8.5, 10 or a little less, 11½ with indications of a second crest, 14, 17 and 19 years. Mr. Schulman's recent analyses have largely duplicated these results but he has gone very much more into detail. He places a strong cycle maximum at 12 years. This will appear in his lists below and in the frequency periodogram prepared by him and shown in figure 55.

Since the curves are not standardized, it was felt that amplitudes obtained by the usual methods would not be satisfactory. So a qualitative idea of the amplitude is given by the underline number, essentially a weight, in column 2. The letter x in that column indicates a weak cycle. One can keep in mind that specimens numbered 1, 2, and 3 were from the greatest depth, and numbers 11 and 13 were lying near the present flat surface of the valley fill.

YELLOWSTONE FOSSIL TREES

In 1929 and 1930 collection was made of some 38 Tertiary sequoias (*Sequoia Langsdorfii*), silicified, from Specimen Ridge in Yellowstone National Park. These fossils were secured by Messrs. Mason and Reade as nearly as possible from one single horizon of petrified stumps. Probably many of them were living trees at the same time. Like the corresponding

Yellowstone Fossil Trees

Cycles, yrs.	Underl.*	Duration, yrs.
1929 #1: 106 yrs.		
6.5	no	106
7.5	no	106
10.1	2	106
12.6	1	106
15.1	2	106
23.6	1	106
1929 #2: 119 yrs.		
5.1	x	119
5.6	1	77
6.3	no	43
7.8	no	103
9.8	1	119
11.8	2	119
15.3	1	119
24.1	no	119
1929 #6: 176 yrs.		
6.4	no	160
7.0	1	56
8.6	2	176
12.5	1	176
14.3	no	176
17.0	2	176
19.5	1	176
#6(2): 72 yrs.		
6.1	no	72
7.5	no	72
9.9	1	72
11.9	no	72
14.3	no	72
18.8	1	72
#6(3): 71 yrs.		
5.9	1	71
7.3	1	71
10.6	1	71
11.7	2	71
14.5	1	71
21.6	x	71
#7(1): 85 yrs.		
8.0	1	85
10.1	no	85
11.8	2	85
14.5	no	85
18.1	no	85
24.1	no	85
#8(1): 184 yrs.		
6.0	1	74
11.4	no	184
12.0	1	184
14.3	no	184
17.5	no	184

Cycle, yrs.	Underl.	Duration, yrs.
#8(2): 118 yrs.		
5.2	x	35
6.4	1	91
7.8	no	94
10.0	no	87
11.0	no	118
12.6	1	101
15.6	x	118
#9: 105 yrs.		
6.3	no	105
7.7	1	73
9.7	no	105
10.4	x	105
11.3	1	105
12.2	no	81
14.6	1	105
22.3	1	105
#11: 154 yrs.		
5.6	x	80
7.0	no	149
8.1	no	89
10.1	2	154
11.4	1	99
13.7	2	144
14.4	no	134
17.4	1	148
20.3	x	144
24.0	no	144
#12: 91 yrs.		
7.0	no	91
10.3	2	88
11.4	1	88
14.1	no	91
16.9	2	91
21.1	no	80
#13a: 60 yrs.		
5.0	no	60
7.0	1	60
9.8	no	60
11.3	1	49
13.8	1	51
#13b: 39 yrs.		
5.2	no	39
7.5	no	34
9.9	1	39
11.7	x	39
#14: 361 yrs.		
5.5	no	144
6.3	no	66
7.5	no	261
11.2	1	361

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* For underlines, etc., see pages 146 and 147.

Yellowstone Fossil Trees—Continued

Cycle, yrs.	Underl.*	Duration, yrs.
# 14: 361 yrs.—*Continued*		
12.6	2	361
17.0	2	361
18.9	1	361
24.0	2	361
#15a: 512 yrs.		
6.1	no	82
8.7	no	451
14.4	2	437
18.6	2	512
#15b: 495 yrs.		
13.7 and	2	473
15.3 or	2	196
14.2	2	473
18.7	1	495
21.8	1	306
#15c: 511 yrs.		
6.8	no	82
7.5	no	219
9.4	no	205
14.3	2	399
14.1	no	112
18.7	1	308
#16: 111 yrs.		
6.1	no	111
8.7	x	111
10.3	no	111
11.6	2	111
14.1	1	111
20.7	no	111
23.9	1	111
#17a: 68 yrs.		
6.9	no	68
8.1	1	68
9.5	no	68
11.6	1	68
15.1	no	68
17.0	1	58
19.2	no	64
#17b: 61 yrs.		
7.2	no	61
10.1	1	61
11.3	no	48
14.6	no	61
#18a: 101 yrs.		
5.8	1	101
7.1	1	101
8.4	1	61
11.6	1	101
14.2	2	101
17.5	2	101
23.9	1	101

Cycle, yrs.	Underl.	Duration, yrs.
#19: 79 yrs.		
5.6	no	79
7.0	no	79
9.9	1	79
11.3	2	79
14.0	no	79
21.9	1	79
#20a: 136 yrs.		
8.8	no	136
14.4	1	136
17.6	2	136
#20b: 124 yrs.		
9.8	no	124
11.8	1	124
14.4	1	105
18.8	no	124
24.0	no	124
#21: 99 yrs.		
6.4	no	99
7.9	no	63
11.7	1	99
13.5	1	99
18.8	1	99
#21b: 105 yrs.		
7.4	1	105
10.1	1	100
11.4	no	83
14.9	1	105
16.8	1	105
24.2	no	105
#21c: 85 yrs.		
5.0	no	85
7.2	no	72
10.0	1	85
12.2	1	70
15.1	x	85
18.7	x	85
#22a: 65 yrs.		
5.2	no	65
7.0	x	65
10.4	1	65
11.2	no	60
17.8	x	65
#22b: 54 yrs.		
5.3	no	40
6.6	1	54
7.8	1	54
9.9	1	54
11.4	1	54

Yellowstone Fossil Trees—Continued

Cycle, yrs.	Underl.*	Duration, yrs.
#24a: 602 yrs.		
6.5	no	602
7.4	no	111
10.1	2	516
12.2	no	221
21.5	no	371
24.0	2	546
#24b: 169 yrs.		
6.0	no	149
7.1	1	169
8.7	no	169
9.8	no	169
12.3	no	169
14.3	2	169
17.1	1	169
20.3	1	169
#25: 238 yrs.		
5.8	1	158
7.2	1	238
8.9	1	238
11.3	2	238
14.5	no	238
17.7	no	238
22.7	2	238
#26a: 125 yrs.		
6.4	no	125
8.7	2	125
10.3	no	125
11.9	no	125
13.7	1	125
16.0	no	125
17.3	no	125
20.5	no	125
23.2	1	125
#26b: 94 yrs.		
6.3	no	94
7.6	no	68
8.5	1	58
9.8	2	94
11.3	no	94
13.5	no	94
20.3	no	94
#29a: 211 yrs.		
7.0	no	173
10.1	1	141
12.5	1	207
14.1	1	207
17.0	2	207
19.4	no	211
24.0	no	211

Cycle, yrs	Underl.	Duration, yrs.
#29b: 200 yrs.		
9.4	1	200
10.1	no	118
12.0	1	200
12.6	no	130
14.2	1	200
15.7	1	200
17.1	1	200
19.0	1	200
23.6	1	200
#30: 176 yrs.		
8.8	1	176
10.0	no	135
17.1	no	176
20.1	1	176
22.1	x	176
#31: 167 yrs.		
9.8	no	167
11.4	1	167
12.5	no	151
14.2	no	121
15.7	no	77
22.5	no	167
#34: 92 yrs.		
5.3	no	92
6.9	no	92
8.2	no	92
10.1	no	85
11.4	1	92
13.7	no	92
17.0	x	80
23.3	no	92
#35a: 186 yrs.		
7.6	2	71
8.4	1	141
10.0	1	186
12.0	1	186
13.2	no	181
14.3	no	186
17.1	1	186
20.1	no	186
#35b: 106 yrs.		
9.1	1	106
10.1	no	106
11.0	2	106
14.4	no	106
18.7	1	106

Yellowstone Fossil Trees—Concluded

Cycle, yrs.	Underl.*	Duration, yrs.
#36: 106 yrs.		
6.5	1	46
8.2	1	87
9.8	1	56
12.2	1	81
19.0	1	106
#37a: 133 yrs.		
5.6	x	133
6.6	no	133
8.5	1	91
12.6	1	133
16.9	x	133
21.0	no	133
#37b: 123 yrs.		
7.0	1	87
9.3	1	114
11.8	no	123
14.0	2	87
14.7	x	123
21.1	no	123
23.1	1	123
#38: 85 yrs.		
7.1	no	85
9.2	x	85
10.2	2	70
13.2	2	85
16.8	1	85
22.0	no	76

species today, the coast redwood, they are cross-dated with difficulty, for there are no distinctive drought rings to serve as guides, such as aid so greatly in the giant sequoias and the pines of drier regions. The counting therefore lacks the precision of cross-dated material, but many duplicate radials were counted and measured and it is thought unlikely that important errors have entered the results. Over 11,000 rings were measured, plotted, and given preliminary analysis by Mr. H. F. Davis in 1932. These analyses were checked and recently repeated in great detail by Mr. Schulman in order to find various statistical characters of the cycles. We all agree on cycle maxima near 8.5, 10, 11½, 14, 17, and 19 years. Some of the sequences gave groups of cycles so closely alike that it may be possible to cross-date by that means.

It was noted that the frequency periodogram of the Yellowstone fossil trees shows great sensitivity; on the whole the cycles in it seem more precise and follow more consistently one configuration than do the cycles in either the 42 Western Groups, the Arizona and California long chronologies, or the California coast redwoods. The newly derived periodogram from the fossil trees shows the 10 and the 14-year cycles to be fully as important as the 11½-year cycle.

It is highly interesting to make comparisons between frequency periodograms from the fossil and the coast redwood. A periodogram of cycles in the latter trees recomputed in accordance with the present reduction methods[1] shows at once a pronounced agreement with the Yellowstone periodogram. Due to the short average length of curves in the Yellowstone group, its periodogram has little weight for cycles longer than about 18 years.

The suggestion is strong in the coast redwoods of a liberal sprinkling of random effects in the cycle configurations, which have averaged out in the periodogram. In striking contrast, there is a near absence of random effects in the Yellowstone analyses. Frequency periodograms are given in figure 55.

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[1] Using the rings in upper levels of the trees because such rings were found to be much less erratic.

ANALYSES OF OTHER GEOLOGICAL MATERIAL

The very remarkable records revealed by Professor Gerard DeGeer in Sweden and Dr. E. Antevs in North America well deserve careful analysis for cycles. Antevs's measurements of the clay layers in the Connecticut Valley, left in the retreat of the New England ice sheet, received a brief preliminary analysis soon after they were published and a recent, fairly complete review. His sequence, examined for cycles, covers about 4000 years with a break in it. Careful cross-dating has no doubt given the separate parts a fine continuity. Cycles between 7 and 8 years in length occur frequently; at 8.8 and at 10 years there are strong cycles; the 11-year cycle is weak or absent; only two good examples of it appear in the 4000 years. A cycle shows at 12.5 years, a group at 13 and another at 14.5, some weak cycles at 16 and 17, and strong cycles close to 20 years. This result is essentially repeated in the 736 years of Hudson River varves, recently published by Dr. Chester A. Reeds, New York.

In 1912 a large number of fragments of swamp cypress, *Taxodium distichum*, described to me as Pleistocene, were secured in the peat beds north of Dresden, Germany. The total rings measured were 1260 in number, distributed in four specimens giving long ring sequences nearly free from errors. One 500-year record gave a strong cycle at 10.9 years; another gave a good cycle at 10.0 years. Others were not particularly satisfactory, owing to the complacency of the growth. These values show resemblance to the varve cycles just described.

Several years ago the late Professor Udden of the University of Texas discovered lamination in anhydrite material forming a drill core brought up from some 1500 feet in depth in Culbertson County, Texas. He became satisfied of the annual character of the layers and with aid of a grant from the Carnegie Institution he had them measured. He thought there might be an error of the order of 2 per cent in layers lost. The longest good sequence of layers studied has 1443 years. The measures were turned over to Dr. E. L. Dodd, whose analyses for cycles showed the presence of cycles of 10, 11, 19, and 33 years. I was fortunate enough to secure a copy of this series of measures and have checked the analysis and confirm Dr. Dodd's results within small differences. I find cycles at 7 to 7.5 years, 8.8, a very prominent Hellmann cycle at 11.4, a group between 14 and 15 years, a faint cycle at 17.5 years, and a little better one at 19 years. I found only a weak cycle at 10 years.

VI. RELATION BETWEEN TERRESTRIAL AND SOLAR RECORDS

EARLY RESULTS

The first measures of tree rings at Flagstaff in 1904 were made for the purpose of finding whether their thicknesses varied from year to year in relation to the sunspot cycle. Six trees were used whose dating was not free from small errors. The measures were smoothed by 9-year running means and a comparison with a similar smoothed curve of southern California rainfall showed some resemblance. This was considered encouraging because the energy used in carrying moisture from the oceans to these forests comes from the sun. In 1906, the ring records of 19 more sections of western yellow pine from locations near Flagstaff were compared with rainfall data in long running means with similar promising results. These comparisons are shown in figure 47.

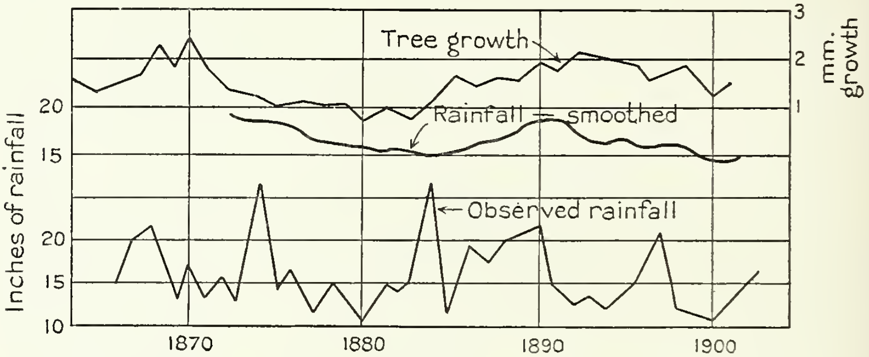

FIG. 47—Arizona tree growth and California rainfall; curves of 1909.

Comparisons with rainfall could only reach back to 1898 near Flagstaff, 1867 near Prescott, and 1851 in southern California, but correlations with solar records could extend back to the beginning of the latter in 1610. Integrations of sunspot data in a cycle length of 11.4 years were compared with similar integrations of tree records (not yet accurately dated), southern California rainfall and temperature. This set of curves, prepared in 1908, gave the first crude record of the Hellmann cycle in trees, as shown in figure 48. In this correlation diagram, two crests appeared in the Arizona trees, two crests appeared in southern California rainfall; one crest and a possible second are seen in the temperature curve and, of course, only one in the sunspot curve. A maximum of tree growth, rainfall, and temperature came near the minimum of sunspots.

In 1911 a full total of about 10,000 ring measures had been made when it was proposed to test what seemed a highly improbable relationship; namely, a linear positive correlation between ring thickness and annual rainfall. After

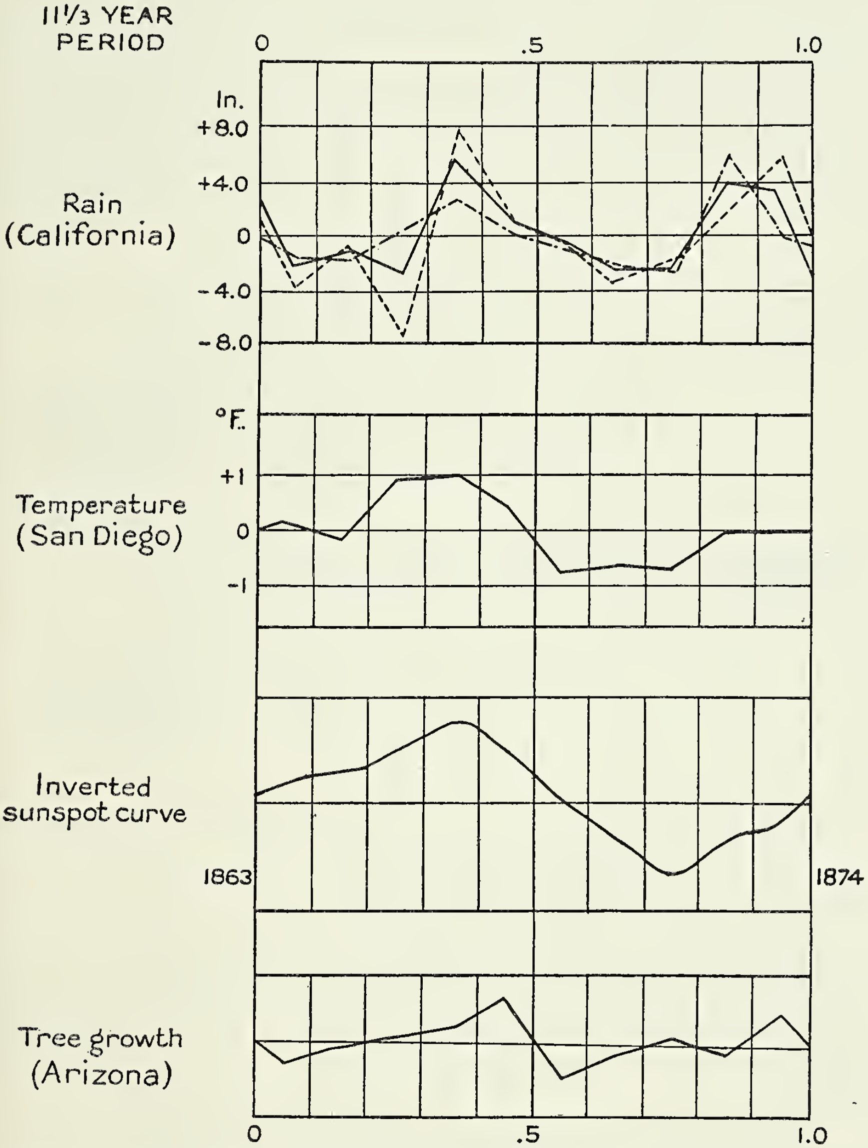

Fig. 48—First western correlations, 1909. The horizontal scale gives proportionate parts of 11⅓ years. Rainfall curves are: dotted line—San Francisco; broken line—San Diego; full line—their average, approx. 1850–1900. Tree Growth, 1701–1906.

adjusting the rainfall year to begin near October of the preceding year, comparisons were made upon an accurately dated group just collected and the agreement was obvious. In the same year, a group of specimens from Prescott was used for special comparison with Prescott rainfall since 1867 and strong correlation was obtained upon allowing a small conservation.

But other developments occurred in the next few years. Late in 1912 an 11-year cycle had been found in German and Swedish trees, figure 51 (2, 9, 10, 11), similar in form to Hellmann's north German curve of rainfall in relation to sunspots. Two of the original sections are shown in Plate 21. North German and Swedish trees showed a single crest, paralleling the smoothed annual sunspot numbers; other curves showed the beginning of a second maximum in growth at sunspot minimum; still others showed this second maximum well developed. The crest at sunspot maximum was evident through a long period of years (1830 to 1911) and thus gave a high correlation with the extended annual sunspot numbers.

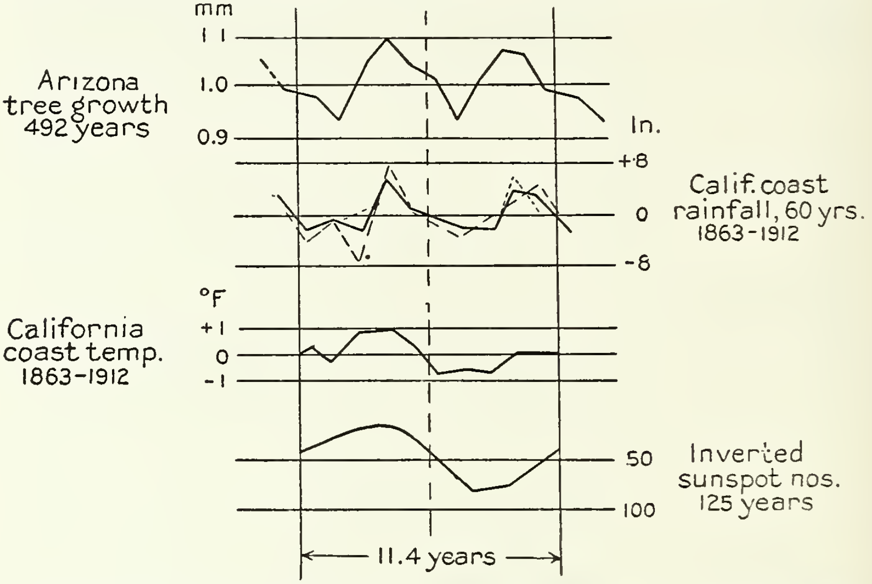

FIG. 49—Western correlations, 1914 in "The Climatic Factor," by E. Huntington.

In the spring of 1913 the Flagstaff trees, numbers 7 to 25, still in hand, were reviewed and corrected as to yearly identity and a new integration made on an 11.4-year cycle, this time with far better success, for the dating was correct. The resulting integration diagram is shown in figures 49 and 50. Hellmann's rainfall curve is included and matches that in California rainfall.[1]

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[1] List of references to extended curves from which the summated curves in figure 51, page 120, were made.

2 (a) Hellmann's curve—Proc. Nat. Acad. Sci., Mar. 1933, vol. 19, p. 354, fig. 6.
3 (j) Flagstaff Hellman—I, p. 102, fig. 32; Proc. Nat. Acad. Sci., vol. 19, 354, fig. 8.
4 (h) Springville Sequoias; not published.
5 (f) So. Calif. rain—Proc. Nat. Acad. Sci., vol. 19, 354, fig. 7; fig. 5.
6 (g) Grant Park Seq.—II, p. 100, fig. 10; measures—I, 122–3.
7 (b) 80 Europ. Trees—I, 78, fig. 26.

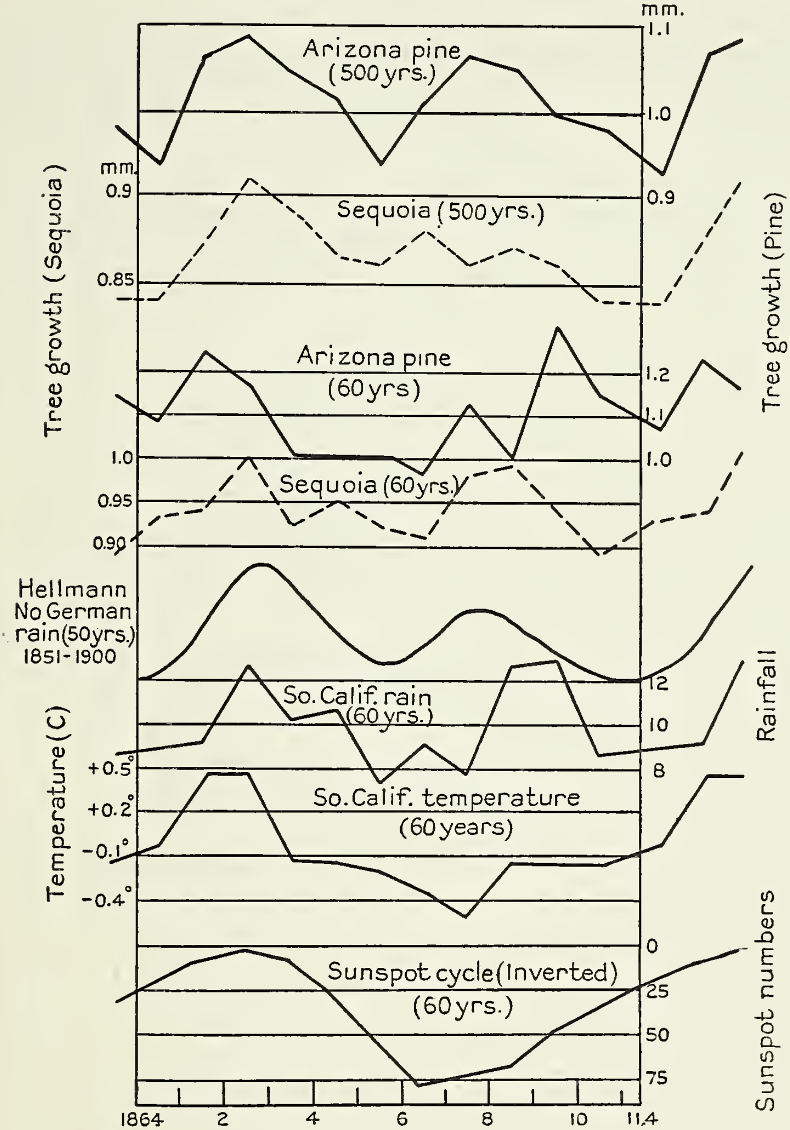

FIG. 50—Correlations, 1919.

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8 (i) Bear Valley, San Bernardino Mts., fig. 5.
9 (c) So. Sweden—I, 75, figs. 22 and 23.
10 (d) Eberswalde—I, 75, fig. 23.
11 (e) 57 Europ. trees—I, 77, fig. 25.

Vermont curve I, 78, fig. 27.
Oregon curve I, 43, fig. 11.

The 80 European Trees (7b) include the 57 selected ones (11e) that formed a separate group. Curve number 7 is derived from the number of occurrences of maxima in the ring thicknesses and not on measures. California rain in curve number 5(f) has the same curve in two amplitudes, the larger amplitude showing after subtraction of interfering cycles. Other extended curves referred to in the text may be found.

It became very evident that improvement in method of cycle analysis was urgently needed. This was accomplished, as related, by the multiple plot and the first automatic periodogram. In 1914, the automatic cyclogram was made.

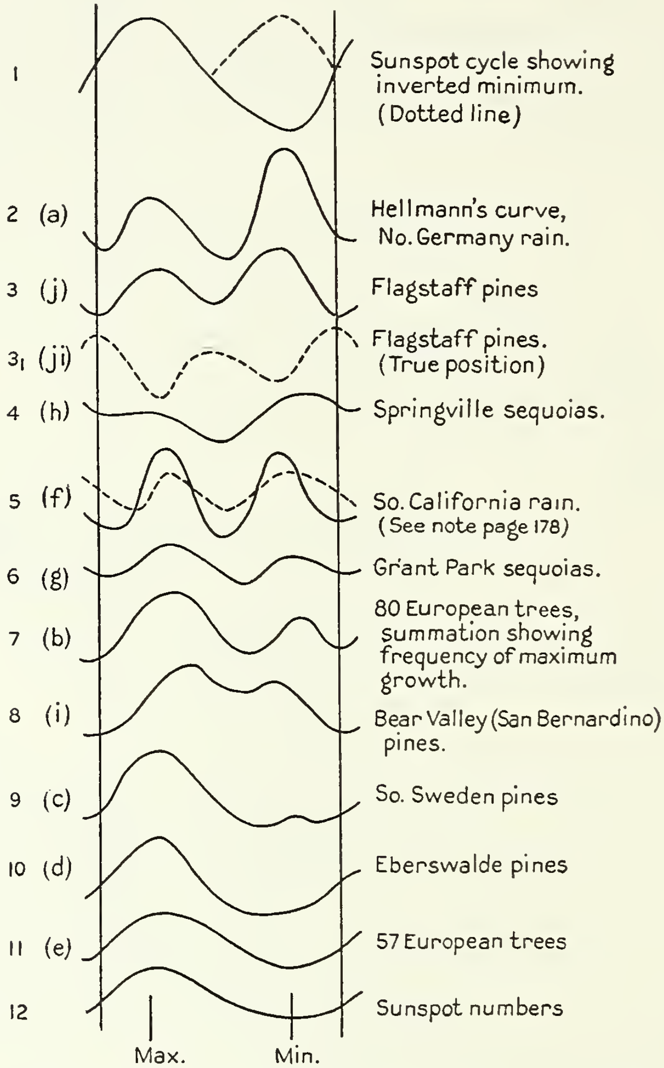


FIG. 51—Integrations on 11.4 years of data mostly between 1850 and 1900; arranged according to prominence of second maximum of Hellmann cycle. See footnote pp. 118, 119.

Then for several years an obstacle seemed to stand in the way of progress; there were too many cycles. The smoothed annual sunspot means had been analyzed and, as we know, a clear, well-defined if somewhat variable cycle was the most conspicuous character; but not so in climatic and tree-ring sequences. Here was a mixture in which, in some places, well-defined cycles stood out, including the 11-year length, but there were many others in addition and apparently of similar importance. The two-crested 11-year cycle, heretofore found by integration, was the gateway into this new forest of almost unknown tree-record cycles.

One of the first uses of the new analyzing method was an attempt to see the cycles in the Flagstaff ring record. A double-crested 11-plus-year cycle was evident since about 1400 except for a considerable interval near 1700. Mention of this was made in *Climatic Cycles and Tree Growth* (1919, vol. I, p. 102). The history of the 11-year cycle is shown in figure 33 and in Plate 12f, of that volume, and in this volume in figure 52; the change and flattening of the 11-year cycle between 1660 and 1725 is evident. As Maunder pointed out in 1922, this coincides with the great dearth of sunspots described by him as extending from 1645 to 1715. In the next few years until 1926, many hundreds of cycle plots of tree-growth curves were made and analyzed without bringing understanding of why so many cycles existed. In 1925, a collection of new ring specimens was made through New Mexico, Colorado, Wyoming, Idaho, Oregon, Washington, and California. The 42 groups, collected

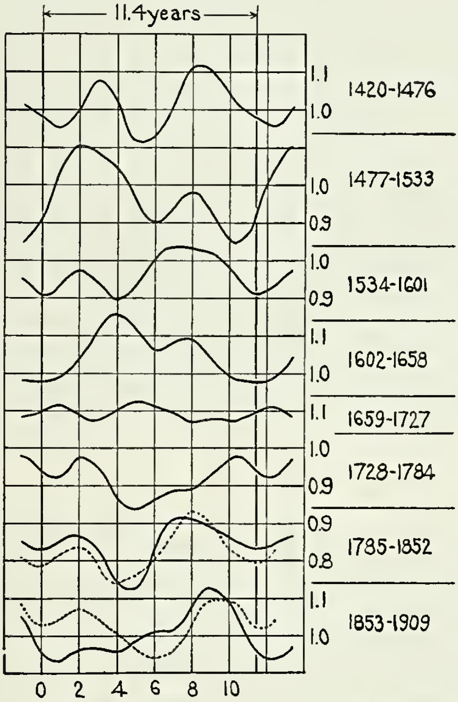


FIG. 52—Hellmann cycle in Flagstaff pines, FLC-FLU, since 1420; averages of five or six successive 11.4-year intervals. Dotted lines show effect of subtracting two interfering cycles, 19 and 13.5 years.

largely on this trip, using 52,000 measures upon 305 trees, were plotted and analyzed in the summer of 1926, and then the next cycle step was made by finding what we have called the "cycle complex" or "family" of preferred or dominating cycle values. Late in 1926, after prolonged study of these analyses, it was recognized that the dominating values in the cycle complex matched the various cycle lengths found in the sunspot numbers and usually bore a simple ratio to the 11-year cycle.

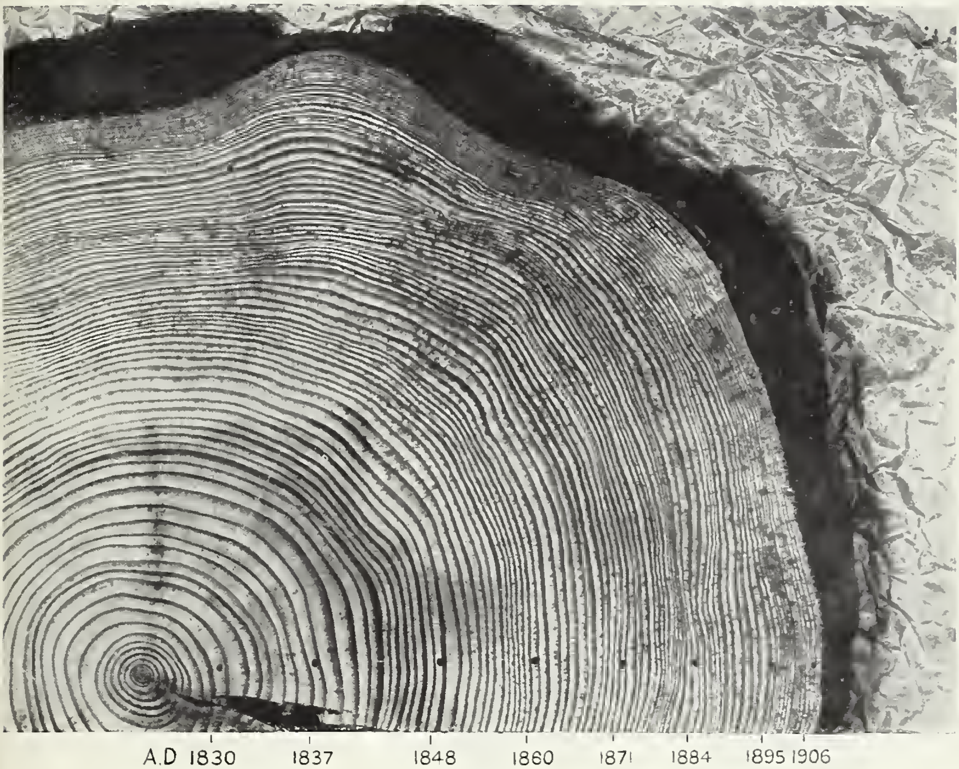
Expressions of this same sort of relation have come from Clayton, Abbot, C. E. P. Brooks, and others. Clayton in *Our Atmosphere and the Sun* finds certain climatic waves that pass across the country and gets evidence of dependence of these on simple ratios of the 11-year cycle. Abbot has found in radiation simple integral parts of 23 years, which is twice the sunspot cycle length, and Brooks has expressed the same sort of thing in connection with studies of the Nile gauge readings during the last thousand years.

EVIDENCE OF SOLAR RELATION IN 11-YEAR CYCLE

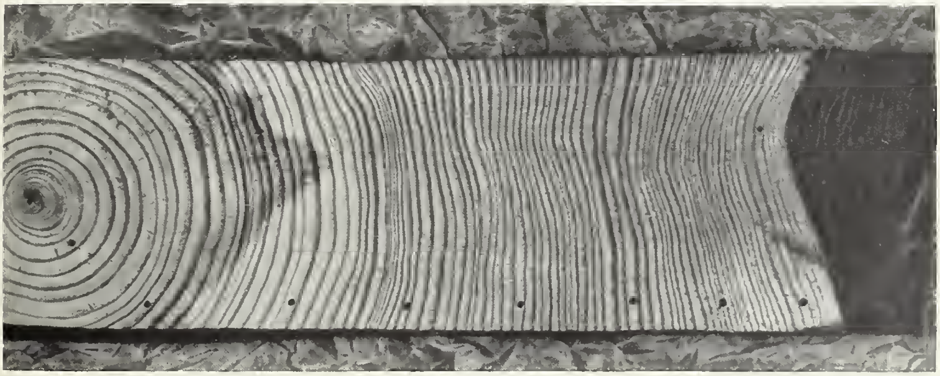
General Resemblance in Cycle Types—There is a general resemblance between tree growth and solar cycles in their discontinuous or fragmentary character. When examined in cyclograms they look alike, save that the former are more apt to have several cycles at a time. This may be persistence of cycles after the cause has changed, possibly a biological character. The persistence may occur in the sun in some form less conspicuous than the usual smoothed annual sunspot numbers; and a part may be considered as related to turbulence in the terrestrial atmosphere.

Evidence by Cyclograms—Difficulty is anticipated here in communicating the evidence we obtain in actual tests with the cyclograph. In spite of general unfamiliarity with cyclogram patterns we feel sure that this method should be used in the present topic because it is by far the most efficient method available. At the start we illustrate the method of reading and interpreting the cyclograms in Plate 22 by reference to an enlargement in Plate 23. Here, as in all cyclograms, each dot or spot represents a full crest in the original curve whose analysis produced the cyclogram. The cyclograph is so constructed that, when set to analyze at a certain cycle length, any series of maxima giving that cycle will take the horizontal position (Plate 23, A–A′). To bring out neighboring cycles the primary row of dots is repeated two or more times in each pattern (Plate 23, A–A′ and A–A′). If a fainter row of dots (B–B′) appears between the main horizontal rows, it means that two crests in the curve rather than one exist in the particular period at which the analyzer is set. The entire series of diagrams in Plate 22 was photographed with the cyclograph set at 11.4 years. Hence one may readily see not only that the 11.4-year cycle is present and dominant but also that in the majority of cases it possesses two crests which, by definition, represent the Hellmann cycle.

If the curve under analysis possesses a period different in length from the one at which the instrument was set, its presence will be revealed by an oblique or secondary alignment (Plate 23, C–C′). The parallel row of dots, D–D′,



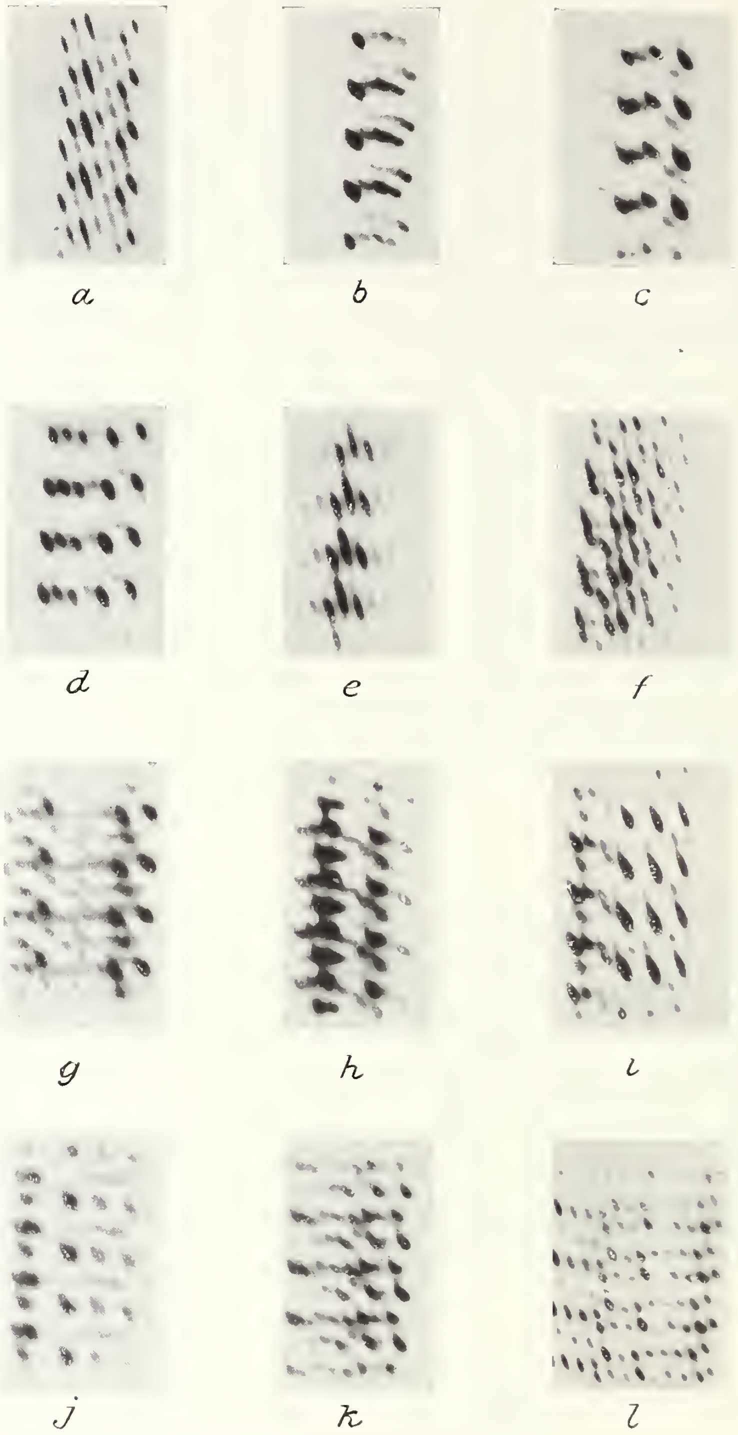
A



B

A. Eberswalde, Germany, ring sequence, G-6; sunspot maxima are marked beginning with 1830; increased growth is found at or following the maxima.

B. Eberswalde specimen, G-2; same sunspot maxima are marked. All rings may be seen on this specimen, ending in the growth in 1912. The tree was cut in November 1912.



Cyclograms showing Hellmann cycles between 1850 and 1900 in Europe and North America, see text. *l* shows an artificial Hellmann cycle produced in solar records by inverting the sunspot minima.

indicates the double-crested nature of the cycle represented by C–C′. In fact, the slant downward to the right in patterns g and m as well as in h, i, j, k, and l, is caused by a double-crested 14-year cycle which, it is evident, exists both in the tree records and in the sunspot numbers. The last pattern, l, is taken directly from the sunspot cycle itself with the minima inverted, which turns it into the Hellmann form. Thus the existence of a Hellmann cycle in any pattern may be judged by its similarity to l.

The 11-Year Cycle and Its Half Value, the Hellmann Cycle—These are so commonly found merging into each other that they must be considered together. The Hellmann cycle was first isolated in Arizona trees in 1908. The full 11-year cycle was found in German and Swedish trees in 1912. Plate 21 shows German trees (at Eberswalde) whose growth follows the sunspot cycle. Forest men in our country have suggested that these effects are due to thinning the forests with characteristic German regularity. On a recent visit there, I was assured by the supervisor of the forest in which the trees grew, Dr. Wittich, that the forest is thinned every three years or so for instruction purposes in the Forest School at Eberswalde. The variations therefore are natural.

Many tree groups show, since 1850, an 11-year cycle with two crests. This cycle in actual length varies from 11.2 to 11.8 years, with perhaps the commonest value at 11.4, which compares favorably with 11.35 years, the average sunspot cycle length since the maximum of 1837. The two crests are somewhat unequal in height and in spacing and in stability. In most cases one crest comes near sunspot maximum and the other near sunspot minimum. The one at maximum seems to be more stable than the one at minimum.

A cycle that fits this description was found by Hellmann in 1906 in North German rainfall; it is shown in figure 51:2(a). Though Hellmann had little confidence in this relation to the solar cycle, it seems to be sufficiently frequent in trees to justify using his name. The existence of this cycle and the others mentioned below is based on the cyclogram patterns in Plate 22, in which the letters correspond to the letters in figure 51.

In Plate 22a and figure 51:2(a), Hellmann's curve of German rainfall is extended to 1920 by the Berlin rainfall record.

In 1912–13 eighty North European trees were sampled. Several hundred dates of maximum growth between 1850 and 1907 are collected in figure 51:7(b) (and Plate 22b), which give the result of this single qualitative test in a symmetrical Hellmann cycle. The only difference from Hellmann's curve is in the greater relative height of the crest at maximum. This curve has been reproduced in extended form in volume I, *Climatic Cycles and Tree Growth*, page 78. The correlation coefficient between full curve and the sunspot numbers is + 0.57 ± 0.07. Extended curves are used here as in each case mentioned below.

Figure 51: 9(c) represents a group of twelve trees from Dalarne, Sweden. The mean curve of the twelve, between 1830 and 1907, based on 900 measures,

places the larger maximum directly at the sunspot maximum; the minimum crest nearly disappears. The extended curve was reproduced in volume I, just mentioned, page 75. Its correlation coefficient with the sunspot numbers is + 0.62 ± 0.06. Its cyclogram is shown in Plate 22c.

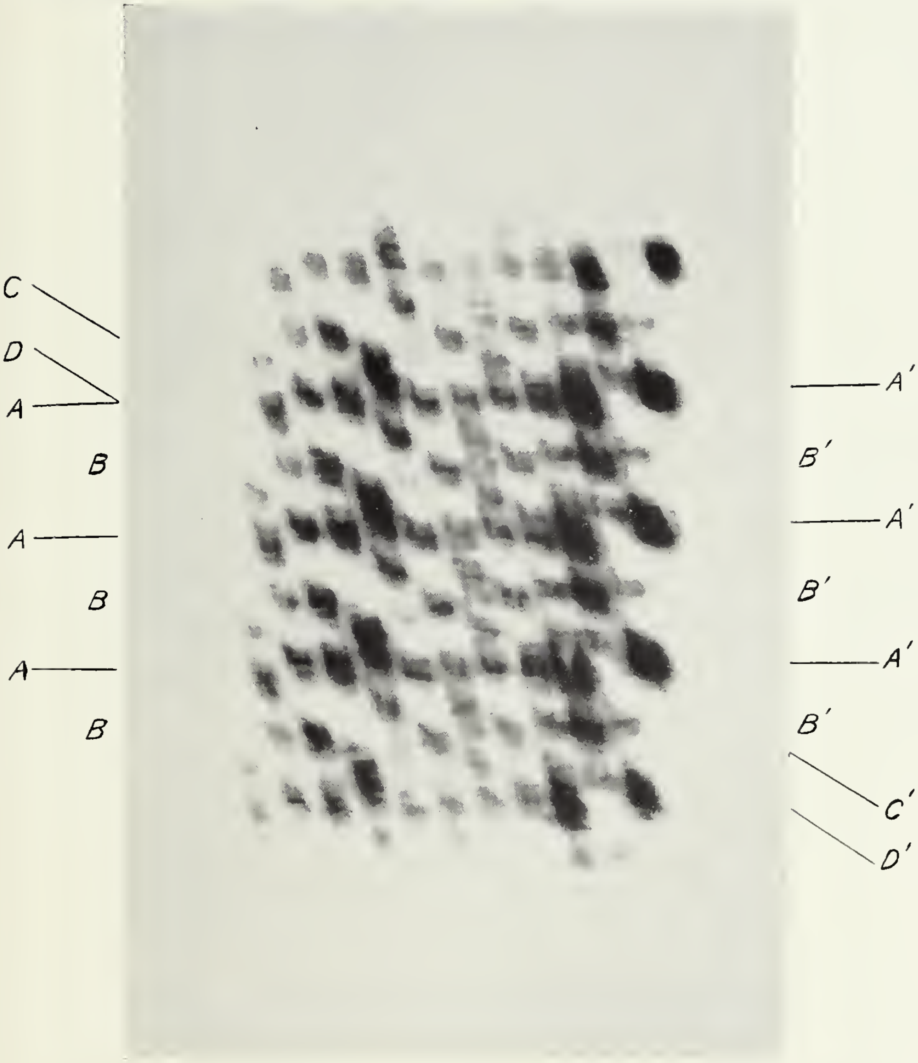
In the important group of thirteen trees from Eberswalde, Germany, 1100 measures, between 1825 and 1907, the crest at minimum has practically gone, except in a very few cases, leaving a massive crest at sunspot maximum, as is shown in figure 51:10(d) and Plate 22d. The extended curve has been reproduced in the same volume, page 75. Its correlation coefficient with the sunspot numbers is + 0.51 ± 0.07.

Six groups, 57 trees, of the nine North Europe groups collected in 1912, when integrated at 11.4 years, show between 1830 and 1910 practical identity with the sunspot cycle similarly integrated, as can be seen in figure 51:11(e) and Plate 22e. This includes about 4500 measures. The minimum crest occurs rarely and disappears in the average. The extended curve has been reproduced in the same volume, page 77. Its correlation coefficient with the sunspot numbers is + 0.56 ±0.05.

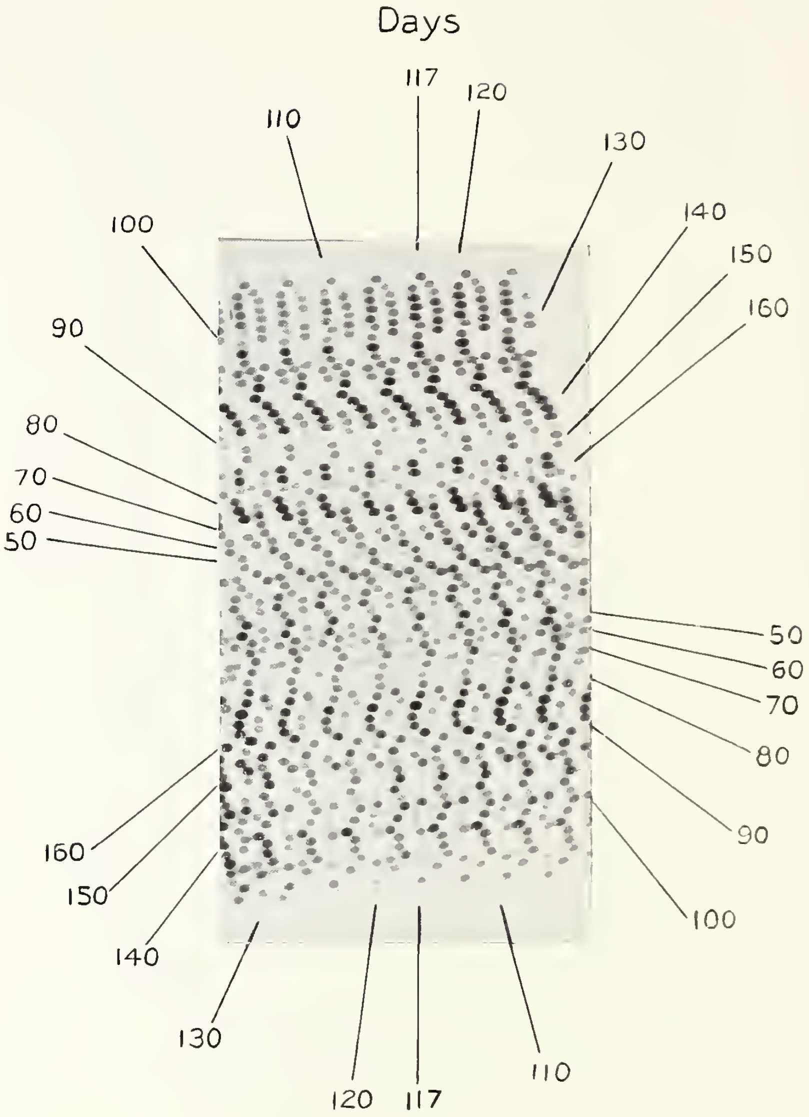
In the United States, a Vermont curve from eleven trees and some 600 measures, 1852 to 1911, shows a strong 11-year cycle with one crest much more prominent than the other, and two or three years phase displacement. The total range between maximum and minimum is about 28 per cent of the mean value. The correlation coefficient is + 0.53 ± 0.06, after allowing for lag of −3 years applied to the solar data. Seventeen Douglas firs on the Oregon coast, 900 rings measured, 1854 to 1910, reach a single-crested cycle with a range of about 10 per cent. There is also a slight lag. The correlation coefficient is + 0.45 ± 0.07, after allowing for a lag of −2 years applied to the solar data.

The largest American groups come from California and Arizona. These are perhaps best introduced by curves of the southern California rainfall, using "Lynch's Rainfall Indices," as shown in figure 51: 5(f), extending back to 1770, a very important and useful compilation verified by the San Bernardino Mountain tree record. These indices since 1850, of course, became actual rainfall records. Smoothed curves of this rainfall have an obvious resemblance to the Hellmann cycle. Cyclogram analysis, 1855–1901, showed interference by a double-crested 14-year cycle and a high amplitude short variation, apparently a little more or less than two years, which causes an apparent scattering of yearly values. Without these the Hellmann cycle becomes an excellent cycle with more than 30 per cent range. See Plate 22f. A study is being made of this two-year cycle.

Figure 51:6(g) shows the Hellmann cycle in the sequoias. This comes from the tabulated means of eleven trees, about 600 measures, published by the Carnegie Institution in 1919. The data originally covering 1810 to 1914 have been extended to 1930 by collections in the Sequoia National Park. The trees are complacent and the range is small; namely, about 8 per cent. But the maxima are clean-cut and the crests are very stable as there is little



Enlargement of cyclogram Plate 22 g, showing Hellmann cycle in sequoias. AA′ and BB′ give the Hellmann cycle with its two crests; CC′ and DD′ show a 14-year cycle with two crests.



Cyclogram analysis of SS Cygni (1918). Data cover 1896 to 1917. Directional values given in days, best seen by looking along pattern at low angle.

interference from longer cycles. A cyclogram study of this sequoia record extended back to 1804 is shown in Plate 23, which is an enlargement of Plate 22 g.

Figure 51:4(h), Plate 22 h, show the Hellmann cycle in the southernmost sequoia grove, south of Sequoia National Park and near Springville, where three 3000-year trees have been found. The curve is made from 500 measures covering 1805 to 1890. The topographic conditions are good but not the very best obtainable for a climatic record, since the area on which the trees grew is rather flat and the ground sometimes very moist. The altitude is high enough for large quantities of snow in winter. After removing a 19-year cycle by mathematical methods, the Hellmann cycle is evident with a range of 15 per cent.

Figure 51:8(i) shows the Hellmann cycle in the San Bernardino pines, derived from 800 ring values, about 1850 to 1900; Plate 22 i uses the larger interval, 1825 to 1925. The trees grew at about 6000 feet elevation in Santa Ana Valley, northeast of Redlands. Collection and measurement of this group was made with the generous help of Mr. J. J. Prendergast, President of Bear Valley Mutual Water Company. After the subtraction of a strong 14-year cycle the Hellmann cycle shows a range of 16 per cent, and probably more.

The Hellmann curve in the Arizona pines, given in figure 51:3(j), and Plate 22 j is derived from 3000 measures in 58 trees, distributed across two hundred miles of country, approximately including 1850 to 1905; the cyclogram, Plate 22 j, uses the interval 1825 to 1920. A 19-year cycle lasting since 1800 completely dominates the record. This and a 14-year cycle were removed by mathematical methods, whereupon the Hellmann cycle was well marked in the curve. It seems to show a lag of two or three years in relation to sunspot phase. It should be added that some of the individual groups in this large assemblage of trees, such as the one from the Grand Canyon, give the Hellmann cycle in prominent form without the interfering cycles.

Plate 22 k shows Grand Canyon tree growth from seven trees, 1825 to 1920. The effect is here shown of using the center of gravity of the maxima, which produces a Hellmann cycle of very good form. There is the same probable two or three year lag, as in the general Arizona curve. A lag of −3 or −4 years fits many of the curves very well (tree-growth maxima preceding sunspot maxima).

Plate 22 l, as already mentioned, gives a cyclogram of the sunspot numbers in which there is an inversion of minimum values for comparison with the Hellmann cycles from terrestrial sources. In general we find that the Hellmann cycle is common in trees since 1850 and that the interfering cycles, 14 and 19 years, are widely distributed. The shorter one is plainly a solar cycle, as will appear later, and the longer is probably so.

Dearth Cycles—The dearth of sunspots is given by Maunder as 1645 to 1715, during which time spots were very rare; two intervals of ten years and four or five of five years show no sunspot records at all. (See pages 68 and 69.) In the 1400's and 1500's, before the dearth, the Hellmann cycle is well developed in the Arizona pines and appears weakly in the sequoias. An 11-year cycle reappeared in good form after 1760.

During the dearth the Arizona trees show a 10-year cycle; four sequoias, which generally show pronounced 11-year cycles, really give a 10-year cycle, which according to Schulman is 10.5 years followed by 9.7 years, giving an average close to 10. Many sequoias show cycles at 8.5 and about 14 years. A long hemlock record in Vermont gives 20 and 28 years with probable half values at 10 and 14 (see vol. II, Plate 9).

Summary—In summarizing the cyclograms of Plate 22, we observe that they show the Hellmann cycle by double horizontal rows repeated four or five times. The fainter row, which is visible in most of these patterns, means that the 11-year cycle is cut into two parts by an additional crest, usually slightly non-symmetrical either in spacing or amplitude. The earlier diagrams, mostly foreign, show the Hellmann doubling less well developed than the American curves, and one remembers that the German trees follow the sunspot cycle mostly without the second crest. In the later diagrams the similarity to the sunspot cyclogram using inverted minima (l) is very evident. This comes not merely in the two lines of crests in 11+ years but also in the secondary double-crested cycle at 14 and 7 years. Note especially the agreement of this secondary cycle in trees with the well-marked 14-year and 7-year lines in the sunspot numbers (with inverted minima) in l. This shows well in all the American trees. Considered historically the dominant cycle, 11 years, varies in similar manner in the trees and the sun. The minor cycles, $8\frac{1}{2}$ and 14 years, are generally present in each. The presence of these cycles in the sun is shown independently by cyclogram process and by Schuster's periodogram, as appears in figure 55.

LONGER CYCLES

Early analysis (by inspection) of the Flagstaff 500-year tree records (1909) gave a cycle of about 21 years since 1700. This has remained very prominent in the last 200 years of Arizona tree growth. In various curves of cycle intensity (periodograms) a considerable crest from 19 to 22 has been evident. There has always been uncertainty regarding the real length of this cycle. A series of integrations at 18, 19, 20, 21, and 22 years, in figure 16, gives 20 years as a good average value of its length. The best mean values from 1700 to 1920 were sent to Dinsmore Alter, who subjected them to periodogram analysis in a rapid and skilful mathematical attack. His correlation periodogram of this sequence is given in figure 53, which shows a strong crest at something over 20-years lag, with further conspicuous crests of about 40- and 80- and 120-year lags. This indicates a 40-year cycle and probably one of 20 years. A cyclogram made of the same data is represented in Plate 16B, which shows at once that this 20-year cycle is composite during this 220-year interval. Through the first one-third, a cycle of about 23 years is prominent and in the remainder a strong 19-year cycle appears, each of which probably lasts through the entire data. This puzzling but strong cycle near 20 years seems to be a composite of two taken in succession.

A curve of Arizona tree growth plotted at 1/5 horizontal scale for 1200 years shows approximately five times the sunspot cycle from A.D. 1168 to 1512. (See fig. 54, page 128. Note the 11-year subdivision in the figure.)

Certain long cycles in terrestrial records could easily result from interference between short solar cycles already mentioned. In the solar records we have the Hellmann cycle and also a cycle at $8\frac{1}{2}$ years; the interference time between these two is 34 years, which gives us the Brückner cycle, frequently observed in tree growth. It is mentioned by Dr. Dodd as present in Udden's anhydrite measures from Texas. The interference between 14-year cycles and 11.4 is about 57 years. The Arizona trees show a strong cycle of this length. The interference between the most common values of the 10 and 11-year cycles (about 10.3 and 11.4) is closely 100 years. This cycle was noted by Michelson in his analysis of the sunspot numbers. Many years ago it was found by the writer in Huntington's measures of the big sequoias as very prominent for nearly 2000 years. Later it has been confirmed, and now is being studied, in accurately dated sequoia records. In the 1900-year Arizona pine record, a 100-year cycle is very prominent, indeed. All these scattering items sustain the idea of a relationship between variations in the sun and in tree growth.

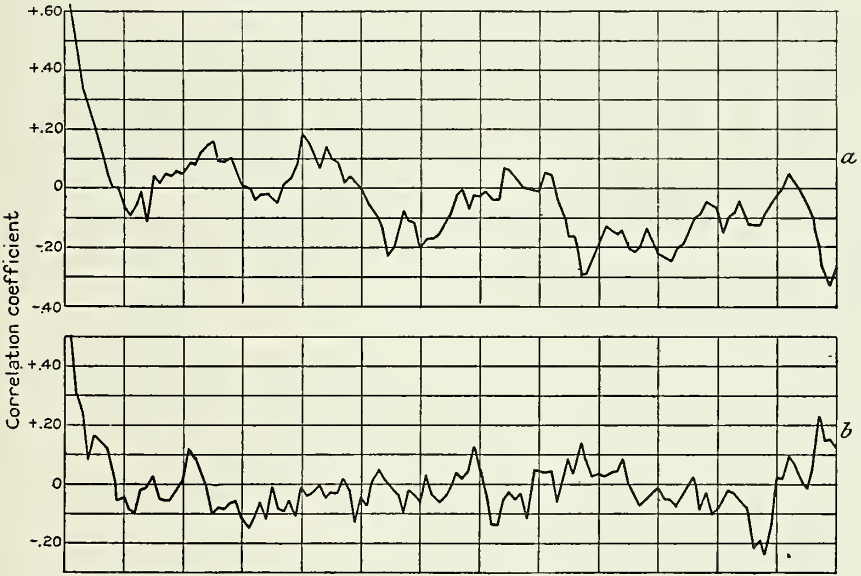


FIG. 53—Correlation periodograms (Alter) for—
(a) Arizona trees, 1700–1920;
(b) California and Oregon trees, 1700–1920.

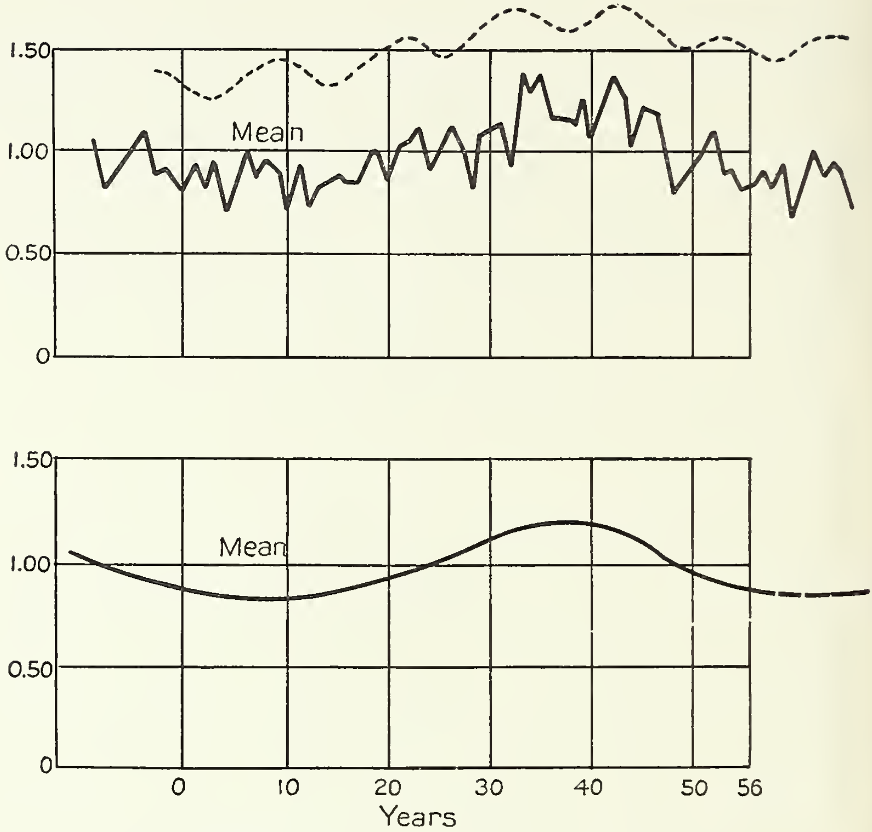


Fig. 54—57-year cycle in Arizona trees, A.D. 1168 to 1503.

FREQUENCY PERIODOGRAMS AND THE CYCLE COMPLEX

In previous pages we have dwelt upon concurrent variations in solar and terrestrial data that suggest physical relationship; we now consider another sort of evidence in favor of such a relationship. It is the "cycle complex" or the group of cycles commonly found both in tree-ring data and in the sun. This complex is shown in the form of a frequency periodogram which gives the occurrence and weight of various cycle lengths observed. It does not require exact amplitudes and epochs and other data discussed in Chapter V. Between most of our groups and individuals in the western areas, the constants so omitted are in excellent common agreement among themselves wherever cross-identification has been done, because cross-identification itself depends on many of the similarities that determine the length of cycles. The simplification of data in the frequency periodogram greatly enlarges the available material, because we can apply this degree of analysis equally to geologic material whose dating and cross-dating are unknown and to groups of modern specimens whose dating is uncertain.

The frequency periodogram is a summary of certain qualities in a group of data; hence comparisons between periodograms from two sets of data tell us something about the nature of the material in hand. Thus there is no correlation between the periodograms from two sets of random data but the frequency periodograms from two different groups of our tree-ring records give excellent correlation (see page 153). This shows that definite similarity exists over wide areas in those bio-climatic changes that come in time units of five years and longer. Five years in this statement is simply a lower limit resulting from the use of an annual unit in tree growth and its adaptation to our analyzing instrument.

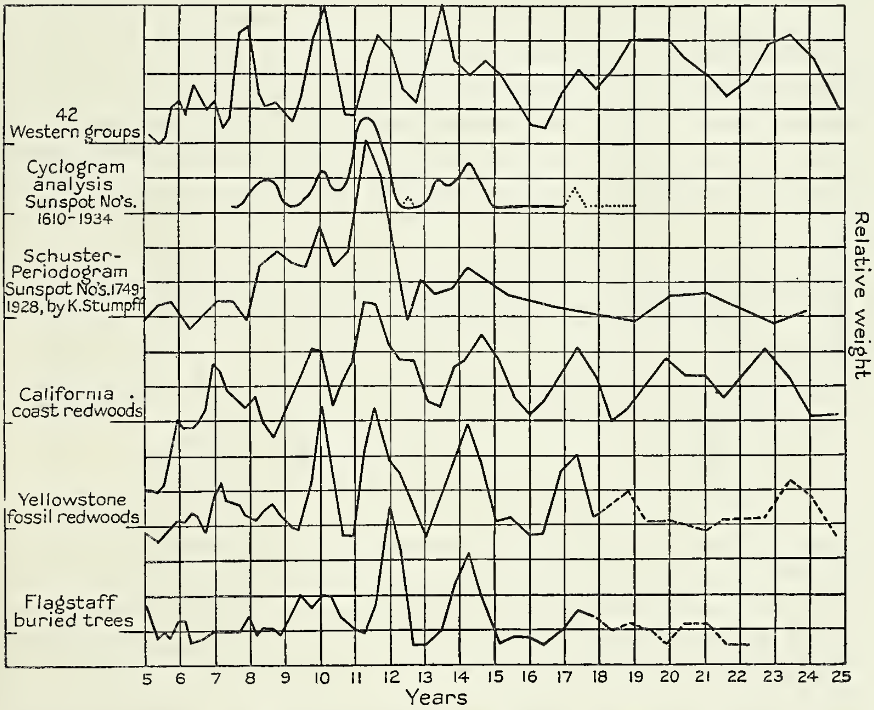


Fig. 55—A group of periodograms to show resemblance of terrestrial to solar cycles.

Certain cycles in this complex were recognized in terrestrial records years ago, such as the 11-year cycle, the Hellmann, a 19 to 21-year cycle, a 35-year cycle, and something near 150 years, all noted by 1909. In 1913, cycles at 8½ years, 14 or so, 22 or 23 were seen. A 100-year cycle came out strongly in the sequoias (Huntington's measures, not exactly dated but compensated for estimated lost rings) in 1915 (vol. I, p. 109). Something between 250 and 300 years has been long recognized in Arizona, especially with the development of the long Arizona chronology.

The complex was named in 1926 when the three western zones were compared in frequency periodograms and their similarity realized. These zones were: first, Arizona, including northern Arizona, and New Mexico west of the Rio Grande, and the southern parts of Colorado and Utah; second, the Rocky Mountain area, Rio Grande, then east to include Pike's Peak and the Rockies north to Yellowstone Park; Sante Fe and points near Mesa Verde were included in this easterly group although they actually show substantial cross-identity with the Arizona area; third, the Coast Zone, including the mountain ranges from points east of San Diego on the south to the Dalles along the Columbia River on the north. The Spring Mountains west of Las Vegas, Nevada, show excellent relation both to Arizona and California.

These different zones were found to give much the same cycle lengths but with different emphasis in weight or frequencies. It seemed probable that the Rockies showed more subdivisions of 34 or 35 years while the Coast Zone made more use of 23 years and its subdivisions and simple fractions. Arizona partook of each, and so the cycle complex as a whole was plainly based on climatic changes over a large and substantial area and not at all on one tree or one square mile or one state. It becomes a terrestrial affair and seems worth testing in all favorable parts of the earth. It has been found strongly evident in the coast redwoods though their dating is less secure. It shows in Vermont hemlocks and in Douglas firs on the Oregon coast.

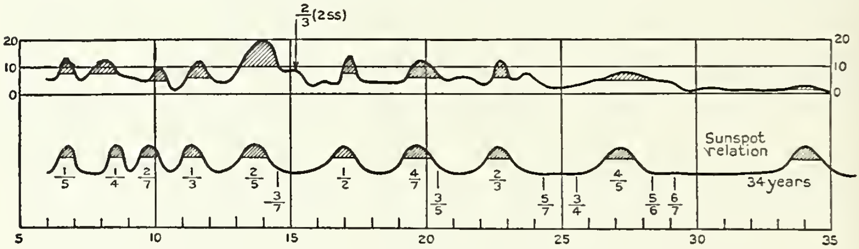


Fig. 56—Western cycles compared to simple fractions of 34 years.

It was then recognized that the cycle lengths appeared to be simple fractions of small multiples of about 11.3 years. Thus it was seen that they included the secondary or lesser cycles observed in the sunspot numbers. This was the result that was checked by the "unknown scale" method (page 47). The correspondence between originals and values obtained at unknown scale has been shown in "Conferences on Cycles," 1929, and the relation to simple ratios of the sunspot cycle appears in figure 56.

Complex from Geological Material—In the last chapter the various groups of geological tree rings or sediments were described and their cycle readings discussed. The various analyses of modern and past climates when brought together show two chief results of interest to us. First, all these terrestrial cycles from geological sources approximate in length the cycles in sunspot numbers as well as did those in modern ring records (see fig. 55); and second, they exhibit the two types of cycle complex or mixture already observed historically in the sun and trees; namely, the present common type in which an 11.4-year cycle or something near that is conspicuous and the dearth type practically without an 11-year cycle and with about the same minor cycles in each group. Figure 55 brings out the agreement found in modern trees in the long chronologies, in buried trees, living perhaps 2000 years ago, in Miocene sequoias from Yellowstone Park, with Schuster's periodogram of the sunspot numbers—an evident similarity outlining an immense interval of time.

But there is evidence that this cycle complex was not continuous from Permian times to the present, for studies of Pleistocene varves and logs of swamp cypress, *Taxodium distichum*, probably of the same age, seem to indicate that the Pleistocene cycles resemble the terrestrial and solar cycles during the sunspot dearth near A.D. 1700, in the weakness of any 11-year cycle.

It is evident that the cycle complex in rings and in annual sediments offer us two or three openings; first, an opportunity of extending to great length our information upon certain climatic changes, both about the earth now and back into past climates; and second, we can reverse our approach to it, as we do in so many lines of knowledge when we have gone far enough to make deductions, and find in our cycle complex in past time the probable length of the sunspot cycle in geological ages. Thus we can form an opinion as to the stability of the sun; and third, it is even possible that with the long chronologies in Arizona and California, covering really a large area, we shall be able by proper comparisons to learn something about the actual dates of sunspot maxima—if not for every one in the last 1900 years, at least for some of them.

PHYSICAL CAUSE OF CLIMATIC CYCLES

The correspondences between solar and terrestrial cycles imply a physical relationship even though it is not yet traced in details. The direct and evident channel of such relation is the heat radiation from the sun that supplies the energy which evaporates water and causes the winds to move it over the land and produce rain. Ultra-violet and other radiation may play an important part in climatic conditions. No one doubts that variations in the heat of the sun can cause variations in the rainfall or other climatic elements. The difficulties have been quantitative: First, that the sun's variations are not great enough; second, that distribution of the effects about the earth would be infinitely complex, and such simple expressions of solar changes would not be isolated sufficiently to become apparent by our measuring instruments.

Neither of these difficulties offers any evidence against a relationship between climate and sun; they are merely signposts with the word "slow" painted on them. And it is well to be cautious, for there are more pitfalls in meteorology than in most sciences (see Humphreys's *Paradoxes of Meteorology*).

Imagine an increase of heat from the sun: Water, land, and air grow warmer, but the air is set in motion and clouds are formed that permit less heat to come through than before the increase. What is the balance of effect? Again, half of the heat received from the sun falls in equatorial regions between 30° north latitude and 30° south. The cloudiness at the poles with ice and snow reduces the effective heat at high latitudes. Atmospheric circulation is induced with the motive force applied in equatorial regions. The earth is rotating and the cold polar areas are small and north temperate zones have continents and oceans. All these conditions make the distribution of solar energy with movements of air and water a most complex operation and many investigators ask why there should be any system anywhere.

Newcomb, thirty years ago, took averages over the earth as a whole and concluded that there was no evidence of connection between meteorological changes and the sun; Bigelow found that solar effects can be positive in some regions and negative in others. That statement of Bigelow's opened the way for tree-ring studies in Arizona and our effort to find the solar cycle in the Arizona trees.

The disturbing feature in all comparisons between solar and terrestrial cycles has been the presence of other cycles on the earth of very different lengths and only rarely one of 11 years. The cyclogram method of analysis helps to solve this difficulty by the cycle complex and its correspondence to actual cycles in the sun. We feel justified in assuming the hypothesis that there is a physical relationship between our climatic conditions and the sun.

VII. THE CYCLE PROBLEM AND LONG-RANGE FORECASTING

THE PROBLEM

In view of the recent great droughts and the need to control erosion and generally to conserve natural resources, scientific thought should be directed to the very important factor of climatic change and any possibility of fore-knowledge or prediction of changes that might affect the value of lands and alter economic conditions.

The problem is this: Can we tell, years in advance, the coming of climatic variations that will have an important economic effect? Can we even improve our present fore-knowledge by ten per cent? The accepted procedure today in attempting to arrive at such long-range prediction is merely to determine an average climatic line (mean rainfall, for example) and the average departure from that mean, and then expect in the future a similar mean and similar departures from it, without knowing when the departures are likely to occur. The question now is: Can we produce a climatic curve of rainfall or temperature or other growing conditions that will reduce the errors of the aforesaid expectation by a sensible amount?

Many attempts to solve this problem have been made without success. It is believed that such failures lie in part in three counts. First: Climatic cycles have been assumed to be permanent, if existing at all, like the annual or monthly cycles that are due to planetary revolutions, whereas, as every investigator has found, climatic cycles do not act as if they were permanent and should be investigated under this corrected view.

Second: The usual methods of search for cycles after failing to recognize this impermanence except in a very crude way, have without justification assumed that the cycles are sine curves, as usually produced by planetary movements, whereas we have no evidence that such is the case.

Third: The mixture of cycles has been too great to be handled by ordinary methods of analysis, which do not recognize the discontinuous period.

The plan proposed below depends on the view that climatic cycles are fragmentary or temporary variations and not necessarily of any definite contour like a sine curve and that they must be extracted from a complex mixture.

In developing a plan we have three aids. First, a similar type of cycle is found in the sunspot numbers and in certain irregular variable stars; second, a different and far more adequate method of analysis has been found in the cyclogram process, by which the length, the duration, and, to a great extent, the contour or amplitude of the cycle may be read off at a glance; and, last, the correctness of a given climatic theory involving cycle solution can only be checked in an immensely long series of data such as thousands of years in which internal evidence can be developed. Because of the discontinuity of climatic cycles we can not, for example, with 49 years of records, tell what the 50th year will be, but with 300 we have a much better chance of estimating the 301st and, better still, with 3000 we can judge the 3001st much more closely. The absolute need of these long sequences has been met to an important extent by the thousands of years of dated tree-ring records of tangible, and, in one case at least, of high rainfall value. With these aids our procedure is to examine first the results in a region where they are best known, and that is in Arizona.

THE ARIZONA RESULTS

These tree-ring records show remarkable similarity to each other over great areas. This is called cross-identity and is due to meteorological effects. The relationship of the ring growth of these trees to winter rainfall is very evident over the period of time in which precipitation records are available. Because of this development of tree-ring records in northern Arizona and New Mexico, the climatic cycles as expressed in rings have been subjected to special study. They form a group called the common "cycle complex" because in analyzing thousands of tree-ring curves both modern and ancient the same cycle lengths are largely found to dominate. These are approximately $5\frac{2}{3}$, 8+, 10, $11\frac{1}{2}$, 14, 17, 19 to 20 and 23 years, not all coming at once. We find that certain of these prevail over the others in certain areas, perhaps due to a selection resulting from degree of water conservation. In Arizona, a 19–20 year cycle has been very strong; the next is near 14 years. When the great Arizona averages, including 50 or 60 trees (Flagstaff Area Mean Curve—FAM), have these two cycles subtracted from them, the double-crested $11\frac{1}{2}$-year cycle that is called the Hellmann cycle is the chief one left. Some of the Arizona groups, such as the Grand Canyon group, show the Hellmann cycle without its being necessary to subtract the longer ones mentioned.

It seems probable that three or four cycles have formed the chief basis of Arizona variations in the last 100 years, at least as far as winter rainfall is concerned, and their immediate application in prediction might be advantageous. There are still three obstacles to the desired fullest solution of the problem in Arizona.

First: These cycles are not permanent and we are not yet certain when any one is going to change. That special phase of the problem is called cycle sequence or recurrence.[1] There is evidence of a long control cycle of about 270 years, in which the shorter cycles tend to recur in orderly sequence. It is especially important to note that these cycles in their discontinuity do not change all at once but rather one at a time; hence, for short intervals of a few years the effect of possible change of one of several becomes actually of less importance than, for example, the two-year cycle mentioned in the next paragraph.

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[1] See Proceedings National Academy of Sciences, vol. 19, No. 3, 359–360, March 1933.

Second: There is a short variation of large amplitude with a length of two or three years. This is well known as the most frequent cycle length found in purely accidental variations and its harnessing into some system must be done with caution. But its consistent dominance in certain form over wide areas gives the impression that it is not accident in the common meaning of that term and that it can be solved. Pending its solution the form for prediction to take, if it is made, will have to be a forecast for the mean of each two successive years instead of for individual years. This amounts to prediction of a smoothed curve.

Third: In this Arizona region the winter rains have been found to give good correlations with tree growth; what about the summer rains? Summer rains have been found to correlate to a degree with tree-ring growth in Florida (Lodewick, 1930). A study of summer rains can be made also in the Arizona trees, for in the case of "double" rings a definite part of the ring is obviously due to summer rains. There is evidence of the dependence of summer rains in part on the precipitation of the preceding winter but, in a more general way, it is probably related to torrid zone conditions.

MISSISSIPPI VALLEY

With regard to great areas like the Mississippi Valley, the problem, it seems to the writer, divides itself into two parts, centering respectively about winter and summer conditions. The activity of winter storms is probably related to the Arizona winter rainfall situation, as both are in the great westerly winds, but the Central Valley has its local records modified by latitude of the mean storm tracks of each season. In this way great complexity is introduced. Any studies that take up, month by month and year by year, the relation between the Mississippi Valley with its complex climatic changes and Arizona with its long and relatively simple records in trees have now an increased importance. Such, for example, are the departure studies now carried on by Dr. F. E. Clements. Measures of rings of trees in favorable localities should be used if possible to establish any climatic connection between these areas in order to use the cycle studies of Arizona for the benefit of the Mississippi Valley.

Summer conditions in the Valley partake of the torrid zone circulation in the summer thunder storm, modified here also by the latitudes of the large cyclonic storm tracks which still persist but lie farther north than in winter.

A summer rainfall maximum of thunderstorm type is so characteristic of Arizona that these summer rains are sometimes referred to as "Arizona rains," but they are more widely distributed than that. They characterize the Great Plains lying on the east side of the Rockies. They are quite evident as far north as Montana. Toward Texas they increase in intensity, taking up more and more of the annual total, thus growing more and more like torrid zone rains. In Texas and northern Mexico they even develop a midsummer minimum that reminds one, and is probably part, of the July minimum between spring and autumn maxima of equatorial regions. Thus it seems highly probable that Mississippi Valley summer rains will be studied in connection with torrid zone conditions and cycles, which may be substantially different from those in the temperate zone.

Thus far we have approached the Mississippi Valley forecasting problem by a method of comparison with Arizona conditions; a method that is indispensable on account of the long records in Arizona. But there is another approach to these Valley variations and that is by tree-ring growth in the Valley itself. In connection with reclamation and power development in certain areas, much-desired climatic work has been carried on by tree-ring methods. Many modern and some ancient specimens have been collected, measured and plotted and compared with meteorological records.[1] Personal examination of specimens has assured me that cross-identification exists to some degree in areas tested, although some of its features depart substantially from the simpler reactions in our dry areas. Though caution is needed in working them out, long sequences of value seem possible of establishment. This conforms with results obtained some years ago by Dr. Robbins of the University of Missouri. Furthermore a direct correlation between Valley tree growth and crops should be sought with care, since its value is more than obvious.

COAST STATES

Regarding the Atlantic Coast states, the situation is in some respects similar to that in the Valley, but complicated by the presence of the Atlantic Ocean, so that a slight change in the direction of the wind may have a far greater effect than in the Central Valley, both in rainfall and on temperature. The latitude of storm tracks is more stable but slow variations in ocean temperatures become a factor. Locations close to the coast are likely to be the most difficult. It is hard to find cycles in the long rainfall records at Boston and New Bedford, Massachusetts, but tree-ring records in 250-year old hemlocks in Vermont and rainfall records close by—Hanover, New Hampshire—give excellent analyses in terms of cycles.

On the Pacific coast the situation is also complicated by the ocean. Precipitation depends extensively on whether storms pass across the Rockies at a northerly point or move down the coast.[2] This perhaps is a latitude effect and may be part of Kullmer's theory. At any rate, there is in California rainfall a short cycle averaging $5\frac{2}{3}$ years and giving the effect which has been named Hellmann Cycle. It has been sufficiently regular since 1851 to give great promise of development as a basis of long-range prediction. But California rainfall values are strongly subject to the two-year cycle of higher amplitude which has a good chance of rendering worthless a predicted annual value. It interferes, however, very little with the prediction of a mean value between each two successive years.

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[1] By Dr. Florence M. Hawley and Mr. Roy Lassetter, students of tree-ring work.

[2] Compare Blake, 1935; see Bibliography.

The Pacific Coast states are especially fortunate in having the longest known dated tree records whose climatic significance has been demonstrated. I refer to the giant sequoias. Sequoias on the high and steep slopes in the upper part of the groves give curves that somewhat resemble rainfall in central and southern California. The Hellmann cycle shows in the general sequoia ring growth curve since 1760. We may look upon California as a very favorable point for early prediction tests.

Of course, these discussions of American climatic cycles are only part of a world problem. What is happening in north Europe when certain cycle conditions exist in America? What in South America, Africa, and Australia? Some day the whole matter will be examined, as it deserves. Inroads into the subject have been made here and there by various students—Abbot, Alter, Clayton, Arctowski, C. E. P. Brooks, Sir Gilbert Walker, W. J. S. Lockyer, C. F. Brooks and others.

RELATION TO THE SUN

It has been stated that climatic cycles resemble cycles found in the sun. This is based directly on the frequency periodograms illustrated in several parts of the last chapter showing that dominating terrestrial cycles have lengths coinciding with lengths of cycles in the sun. Practically the same group of cycle lengths has been found in fossil trees. Coincidence in time of changes in sun and earth has been shown in one case at least (Hellmann cycle in Arizona) but this has not been fully tested in other long records.

The most difficult part of the physical line of cause and effect between sun and trees is the distribution about the earth by atmosphere and ocean, of the energy received from the sun. Since the earth's energy is derived continuously from the sun by some form of radiation, we are justified in holding the hypothesis that the sun's part in the drama of climate is more than the mere exemplification of certain cycles. The resemblance between their respective cycles points directly to the sun's radiation as a cause of terrestrial changes; and once this is admitted, it brings climatic study into close contact with astronomy; the study of the sun and its physical characteristics and mechanical operations become of great economic importance to the human race.

In view of the facts shown by the periodograms above referred to, and from many other reasons for regarding seriously this influence of the sun's energy on the earth, we can form a preliminary climatic hypothesis as an immediate guide in developing the prediction problem along its most favorable lines. This hypothesis may be expressed in three terms:

(1) Discontinuous periods in the sunspot cycle and in other solar activities produce through radiation climatic cycles on the earth of corresponding length. These are disturbed in many places by the complexity of the distribution of solar effects about the earth. Conservation and topographic

characters and perhaps other factors cause different localities to emphasize different individuals of this cycle complex.

(2) For any locality the cycles existing in the last 100 to 300 years, or more, are found and then each cycle still operating is projected forward to construct a curve for a number of years in the future; these averaged together produce a mean which is to be regarded as the expected smoothed value of a few succeeding years.

(3) Less well established but still with some definite foundation in the long chronologies there is the recurrence of several well-defined cycles at intervals of about 270 years. In this recurrence we believe we are finding signs of larger cycles or periods which will aid in removing the uncertainties that result from discontinuity in our climatic cycles.

PREDICTION TECHNIQUE

We feel that prediction and verification in the popular sense can hardly be a reliable guide as to validity of method at the present time. Percentage success or failure is very deceptive when watched for a year or two and means little in such a complex problem. The problem at this moment is not to predict but to lay a basis of knowledge and method out of which conservative prediction will develop. It therefore is best at this time to carry through a prediction process in a crude preliminary way without any attempt to make it exact in the sense of a prediction itself. It merely serves to call our attention to various features that require attention.

Fundamentals of Prediction—The following three classes of prediction are based on a consideration of errors or departures of the subsequent facts from the predictions:

(1) Prediction that the mean value will always occur in the future, let the departures come as they may. This is the kind we find in climatic maps and has its use as important general information.

(2) Prediction on the average departure from the mean, figuring what ought to come if it has not happened recently. This is straight probability prediction from the known distribution of the various departures from the mean, and the probability of any particular value coming next. It is extensively used by engineers.

(3) The third class of prediction is a probability prediction, not from a mean straight line, as before, but from a sliding scale, a variable mean, which embodies climatic cycles as well determined as possible and, if possible, includes a short cycle which we have called the two-year or "scatter" cycle.

In carrying out our plan of illustrating the prediction process, we encounter at once two parts of the problem that need careful thought. At first thought it seems perfectly easy to state the cycles that are operating now. Then we realize that several repetitions are needed to cause recognition of a cycle. The average number involved in recognition is three or four, the average total repetitions before change is eight to twenty. It is a quite important matter to consider how soon an incoming cycle can carry important weight. Some of the recent ring records in Arizona show a five-year cycle operating since 1905. Should we give it full weight? Some cycles are not perfectly constant in length or amplitude. Should we give more weight to the last few repetitions than to the preceding many? It is interesting to note that we have developed a method of trying out questions of this type; the results of such studies will be reserved for a future paper.

The second question naturally is: What is the expectation of continuity after a cycle is established as operating at the present time? When is one of the cycles likely to stop and when is a new one likely to enter? In the case of the sunspot cycle the data show that the intervals between maxima more often than not remain within about 10 per cent of the last value. Hence one of the most important features in our cycle lists (chapter V) is the number of repetitions without material change. That we can be very sure of and by simple methods we can increase our knowledge on that point.

But actual plots (some of them made in 1927) indicate periodic recurrence of certain cycles. Here is the line of most promising development of the theory of climate, bearing upon the temporary cycles that we encounter. That also must be reserved for a future paper.

Cycles in the Pueblo Area—In picturing the situation for a limited area we are taking the only possible course, and no attempt is made to extend consideration outside the "Pueblo" area of northern Arizona and New Mexico west of the Rio Grande Valley and reaching into the southern parts of Colorado and Utah. Having outlined our area we can consider the cycles found there which, together, produce a prediction "mozaic." Considering each cycle as a natural unit of some sort, we wish to take the combination of units operating now and put each unit or cycle one step or cycle length forward. This could be called the "a" stage in the treatment. The "b" stage means weighting each cycle by ascertaining its average number of repetitions in its previous appearances in the last 2000 years and giving it the proportionate part of its average number that remain undone. The "c" stage of treatment is an estimate of its tendency to disappear and its probability of return, derived from the general study of cycle sequence or recurrence from long chronologies. Treatment "d" considers it in relation to cycles of similar or related length in solar phenomena.

It will be appreciated that the above analysis of the prediction problem represents the situation at the present moment. As time goes on and larger areas of the earth are brought under this kind of study, a much better knowledge will be reached of the activity of these cycles and the probability of their continuance or recurrence.

Application to Winter Rainfall of the Pueblo Area—Four or five cycles stand out as more important in the Pueblo Area; 23 years; 19–20 years, one near 14 years, the 11.5-year cycle, and the 2-year cycle. As the unit in tree-ring records is the year, we can not cover very satisfactorily lengths under 5.0 years; certain values between $1\frac{1}{2}$ and $3\frac{1}{2}$ years are derived from the 2-year reversal interference test. (See page 89.) Without doubt still longer cycles now under investigation are equally important in this problem.

The 23-Year Cycle—A cycle of this length and of high amplitude was active during the 18th century. Since then it seems to have given place to a shorter one of 19 or 20 years.

The 19–20-Year Cycle—Several centuries of tree-ring records are necessary in order to get a picture of this long cycle and even now it remains uncertain whether it is not a mixture rather than one single cycle. A cycle of about this length has dominated Arizona ring records since 1800. It shows in recent tree growth and in comparative rainfall records, with apparently a lag of some two years in the tree records. Its last maximum was near 1928; its total range of variation has averaged 35 per cent. In the rainfall records it has been about the same. Its number of repetitions has already run very high and its expectation is growing less. An examination of long chronologies shows that some cycle of this length is very persistent through the centuries though its amplitude is far from constant. It would not be surprising if its time of diminution were approaching. It does not seem likely to disappear altogether. In its solar relation its half value, 10 years, was prominent in the sun (and trees) two hundred years ago. The 10-year cycle, sometimes seen in trees and in various phenomena, and 20 years, and possibly a 37 or 38-year cycle of variable amplitude that persisted for many centuries in Arizona tree records, are probably solar though not commonly in the spots. A 10-year cycle showed in the occasional spots during the great dearth near 1700. It has not, as far as known, come out strongly in recent years. There is some suspicion that a cycle of 5 years is influencing southern California rain to an increasing extent since 1900.

The 14-Year Cycle—This cycle, often double-crested, takes a value near 13.7 years in the last century. Its total range of amplitude is near 25 per cent. It must be studied in trees, since meteorological records do not go back far enough. There are slight alternative choices of exact value in the Flagstaff 500-year records through which it has lasted. Its dominance or intensity varies. A maximum perhaps came in the period 1933 to 1935. This cycle has been persistent since 1850 or so; it possibly changed phase near 1820. In cyclograms it shows extensively by interference with other cycles, giving the impression that we may be dealing with a submultiple of a longer cycle.

As to phenomena in the sun, a 14-year cycle was most evident in the smoothed annual numbers between 1788 (maximum) and 1837 (maximum), the last cycle in this interval being 7 years in length.

The 11½-Year Cycle—This has appeared in a double-crested form in trees since 1850 or before with a total range in amplitude of 20 per cent; its maxima have come in the ring sequences about two years after the maxima and minima in the sunspot numbers. It has had various appearances in California ring chronology that suggest a 270-year recurrence cycle. At each appearance it has lasted a considerable period, of the order of 100 years. Thus at the present time we can cast this Hellmann cycle forward a half or whole 11 years length with the feeling that the length or intensity has a change in the not distant future.

Probably other cycles both longer and shorter could be included in this list, but the various cycles mentioned, when assembled into a picture, give us at least an idea of the prediction mozaic.

The exact outcome of this mozaic is not important since we have not finished testing our hypothesis; but the advance of technique developed by carrying forward this process is most important. Such questions as these arise: In casting forward the observed cycles, should we give more weight to the latest cycle data than to past series of cycles? What is the practical rate of increase of weight from the past toward the present? How far can we rely on recognition of cycles that may be just beginning? What is the last word on the expected number of repetitions of each cycle operating? Is this number constant through history or not, and how does it change? We see a need for investigating dominating cycles: Should a subtraction process be used in isolating cycles; what value should be given to weak cycles? Why do some curves give most satisfactory sets of cycles and others not? Answering these questions in a more or less complete way will rest in further studies of the long chronologies which were largely developed for that purpose. We have even planned a definite method of attack on these questions in a process which we call "laboratory prediction." Experience has shown that as these methods go forward, further improvements will develop. These long chronologies also supply data which we believe will enable us to locate phases of the sunspot cycle in past history. We recognize also many studies to be made on the relation of solar changes to tree growth since the invention of the telescope in 1610.

By outlining the process as done herein, we find the data that need to be observed more carefully. We shall gain knowledge and skill both from historical studies of the past and more intensive work on the present. In the course of time, the action of these climatic cycles will be known in more and more detail, and long-range forecasting will improve. It will not be good sense to look for accuracy at the start, and for some years verification of error must be taken as merely so much scientific information that merges into and improves the method.

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APPENDIX

STUDIES OF THE CYCLOGRAPH

By Edmund Schulman

INTRODUCTION

The cyclograph is an optical-mechanical instrument to aid in the detection of cycles in variable phenomena. When plotted in a curve, data of this type are transformed by the cyclograph into a pattern whose interpretation by the observer represents a cycle analysis. This pattern is highly sensitive to changes in position of moving parts of the instrument and thus enables analysis over a continuous and large range of cycle lengths. The readable display in the pattern of complex and frequently hidden changes in the character of cycles in natural phenomena makes cyclograph analysis not only a rapid but a highly powerful method, in solving many cycle problems such as those encountered in climatic studies.

However, since the cycle results are obtained by interpretation of a pattern, it is relevant to inquire how much the personal element influences the results. The comparison of the analyses of two or more independent observers is thus indicated. The following discussion is principally concerned with such an investigation; some studies which are in part supplementary to similar material in Chapter II of this volume are also included.

DESCRIPTION OF THE INSTRUMENT

The cyclograph as used at present in the Tree-Ring Laboratory is substantially the same as described by Dr. Douglass in 1915, 1919 and especially 1928 (see Bibliography), although some minor modifications were introduced in 1931–32. In skeleton outlines, the instrument has three major parts.

(1) *The Light Source*—This consists of a horizontal series of light bulbs, in back of which is a mirror, and in front of which is a diffusing screen. This screen forms a window, measuring 44 inches horizontally by 3 inches vertically, in which may be placed for analysis a cycleplot[1] of any curve. All the holes in the cycleplot therefore receive a uniform illumination.

(2) *Movable Mirror Carriage*—The mirror carriage is suspended from a two-rail track which is 7 feet above the floor and runs about 40 feet horizontally, beginning some 6½ feet from the window. The carriage holds two mirrors, 5.5 inches by 25 inches, each inclined 45 degrees to the vertical with the reflecting surfaces toward each other and facing the window. Since the

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[1] A curve plotted on opaque paper, and maxima cut out. See pp. 44 and 149.

top mirror is on a level with the light source, and the lower one is on a level with the object glass of the analyzing box, running the carriage out or in has the sole effect of changing the object distance without disturbing the optical axis. The carriage runway is calibrated in terms of standard scale (see p. 44).

(3) *The Analyzing Box*—Facing the movable mirror is found the analyzing box, which contains most of the working parts of the instrument. The objective is a Tessar II B lens of 6 inches focal length, directly in front of a negative cylindrical lens of 12 inches focal length, whose axis is horizontal. Therefore all rays in the horizontal planes come to a focus at 6 inches from the objective, while rays in vertical planes focus at 12 inches. The image formed by this system at the 6-inch focal plane consists then of a reproduction of the holes in the cycleplot with respect to horizontal spacing of the centers of gravity of the holes, but with the images in the form of parallel vertical bars of light; the width of any bar depends upon the width of the corresponding maximum and its light intensity upon the amplitude of the maximum. This image of parallel bars is called a "sweep" or a cylindrical pattern.

In the focal plane there is placed an analyzing plate consisting of two glass plates having alternate transparent and opaque rulings, whose grating constant is 0.02 inch. Superposing the two plates makes possible any size of transparent line up to 0.01 inch, the total spacing of a pair of successive transparent and opaque lines being constant at 0.02 inch. As arranged at present, the width of a transparent line is closely 0.001 inch. The analyzing plate is inclined at an angle of 17 degrees to the vertical sweep lines. It is then easily seen that the analyzing plate breaks up every vertical bar of light into segments, some of which are permitted to pass through, and some of which are held back. The resulting pattern is a series of light images or dots in several duplicate horizontal bands or sets. With a total effective rectangular aperture behind the focal plane of 0.4 by 1.5 inches, the longer side horizontal, an inclination of 17 degrees, with the analyzing plate used, yields almost exactly five of these horizontal bands in the pattern. A thread is placed in the focal plane to indicate horizontal direction.

Behind the analyzing plate is a condensing lens system consisting of two cylindrical lenses of 6 inches focal length with their axes vertical. Near this system is a small mirror set at an angle of 45 degrees, which throws the light to one side to an observer who views the pattern through an eye lens. The observer then has the cycleplot window to his left and the movable mirrors to his right, while he is out of the direct line of the rays. For photography, the small secondary mirror is swung out of the way and the light allowed to proceed directly to a camera compartment.

When the mirror carriage is moved, the object distance changes and, of course, the focal plane will suffer a corresponding slight change. To keep the position of the focal plane constant, the lens system of the analyzing box, consisting of Tessar lens and negative cylinder, is mounted on a movable frame which receives a slight motion from an arm resting against a spiral wheel. This wheel turns by means of a gear meshing with a toothed runway, which in turn moves at a rate that is a small ratio of the motion of the mirror carriage. The resulting motion of the objective is then such that the change of object distance is exactly counterbalanced and the focal plane remains fixed.

OPERATION

Calibration—Periods in the cycleplot may be made to give a horizontal alignment of dots in the pattern by the simple process of changing the distance of the movable mirrors. With a series of artificial curves having regularly spaced maxima plotted on the normal scale of a unit every two millimeters, it is possible to calibrate a scale marked on the carriage runway so that the cycle length corresponding to any horizontal alignment may be read directly. The cyclograph is calibrated from 5.0 to 42.0, the smallest division being 0.1 unit.

Nature of the Pattern—If the cycle present in the data is not exactly periodic, that is, with all the maxima equally spaced, then since there exists a mean length of the cycle there will be a mean alignment in the pattern. Departures from this mean horizontal position of the dots indicate a slight lag or advance in the occurrence of the maxima concerned; hence, the term *differential* was at one time applied to the pattern obtained. The closer the clustering of the light-dots about the straight line, the closer the cycle approaches a perfect cycle or periodicity. It is analogous to the clustering of dots about a regression line in a scatter diagram as a measure of correlation, though the cyclogram pattern itself is more closely akin to the O–C diagram (in which positions of the dots along a horizontal line represent their theoretical or *computed* places, and the vertical displacements from this line the *observed departures* from exact periodicity).[1] It is evident that a change of period in any interval will be represented by a different trend in the corresponding interval in the pattern, demanding a different position of the mirrors to bring that interval into horizontality. Logarithmically varying cycles will thus form a curved line pattern.

Procedure in Analysis—Two complete analyses of each curve are made, one with the movable mirrors at successive settings from 5 to 42 units, and the other with the mirrors returning from 42 to 5. The items usually noted are cycle length, duration (dates of beginning and ending), emphasis or cycle strength, fractionization or splitting of cycle into one or more series of subordinate crests, phase changes, changes in length or amplitude and any special characteristics.

The matter of cycle emphasis needs particular consideration. The importance or strength of a cycle is indicated by underlining the figure representing the cycle length, very good cycles receiving two or even three underlines (see page 147). The factors determining the assignment of underlines are regularity of period, number of maxima, regularity of amplitude, strength of amplitude, kind of fractionization if any, and freedom from ambiguous maxima and alternative settings.

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[1] In the cyclogram, departures from exact periodicity are also indicated by displacements from a horizontal alignment, but maxima are plotted in their *observed places* in the time scale.

CYCLOGRAM FORMULÆ

A cyclogram pattern may show harmonics arising from two fundamentally different causes. In one case the harmonic is only apparent and arises from a fractionization of the pattern due to a fractional setting; in the second case the harmonic actually exists in the data under analysis.

Harmonics Due to the Cyclograph—The following criterion may be used for judging the fractionization of a setting. If the movable mirrors are set at a point on the scale, i/j of a cycle length existing in data plotted at normal scale, i/j being a simple ratio, then there will be i times the normal number of horizontal rows in the pattern, every row consisting of a series of light dots located one to every j successive lines of the analyzing plate.

It has been found in practise that with the exception of settings at $\frac{1}{2}$, $\frac{1}{3}$, $\frac{2}{1}$, and rarely $\frac{1}{4}$ and $\frac{3}{1}$, the effect of harmonics and multiples is negligible, and these when they occur can easily be recognized. It is possible that the less simple harmonics determine to some extent, however, the apparent presence in real data of subordinate, weak cycles which may not be real.

Harmonics in the Data—Consider an arrangement, with a 12.0 unit standard cycleplot in the window, the mirrors set at 12.0; then the pattern consists of five horizontal rows of light dots.

Suppose we replace the 12-unit standard with any other cycleplot, which also contains a 12-unit cycle and, in addition, a set of secondary maxima of smaller amplitude spaced half-way between the major maxima. We now find double the number of rows of light images in the cyclogram, every other row being relatively faint. Two secondary maxima will give two fainter companion rows of images. The departure from a straight alignment of the rows of dots of course measures the departure of the cycle from a perfect cycle or periodicity.

It is important to note that the secondary maxima will not be of as great a mean amplitude as the fundamental. They may exactly divide the space between the fundamental crests into 2, 3, 4, . . . n parts depending on the number 1, 2, 3, . . .(n-1) of secondary maxima, in which case there will be 5n equally spaced rows in the pattern, or they may directly follow or precede the fundamental, in which case there will be 5 similar *sets* of rows, the arrangement of rows within the set depending on the positions of the secondary maxima. Again, departure from straight alignment will depend upon departure of the maxima from exact spacing.

Alignment Formulæ—Since cyclograms may be observed at all scale settings between 5 and 42 units, the inclinations of cycle alignments in the pattern change with the setting. Let origin of coordinates be at intersection of a sweep line, analyzing line, and a horizontal cross-hair. Consider the rectangular coordinates of the adjacent light dot in any alignment with reference to the cross-hair as axis. Then it is easy to show that the angle of inclination θ of the alignment is given by

$$\tan \theta = \left(1 - \frac{p}{c}\right) \tan i \tag{1}$$

where i is the inclination of the analyzing lines.
p is the period length of the mirror setting.
c is the cycle length represented by the alignment.
From (1) we have

$$c = \frac{p \tan i}{\tan i - \tan \theta} \tag{2}$$

If the sweep lines are inclined at an angle ϕ to the horizontal cross-hair[1] we have the more general case

$$\tan \theta = \frac{(c - p) \sin \phi \sin i}{p \sin (\phi - i) + (c - p) \sin \phi \cos i} \tag{3}$$

and

$$c = p \left(1 + \frac{\tan \theta \sin (\phi - i)}{(1 - \cot i \tan \theta) \sin \phi \sin i}\right) \tag{4}$$

With $\phi = 85°$ and $i = 102°$ as in cyclograms in this volume (4) becomes

$$c = p \frac{1 - 0.09 \tan \theta}{1 - 0.21 \tan \theta} \tag{5}$$

CONSTRUCTION OF FREQUENCY PERIODOGRAM

To produce a periodogram summarizing the analyses of a number of curves, the procedure is first to make up a cycle diagram (see fig. 57). Each cycle in every analysis of the series is entered in the diagram with its weight, the numerical value of which is that given in the following table. To expedite the formation of the diagram, the cycle weights are sometimes represented by symbols as follows:

Type	*Underline*	*Weight*	*Symbol*
Poor	x	1	– dash
Normal	no	2	. dot
Good	1	4	x cross
Excellent	2	6	⊕ circled cross

A plot is made on the standard 2-mm. graph paper used in the Laboratory; cycle lengths, one scale unit per centimeter, are plotted as abscissæ, the smallest interval recognized being one-tenth unit. It is then easy to sum up the columns, mentally transforming symbols into numbers, and obtain a set of periodogram numbers. These when plotted form a weighted frequency periodogram.

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[1] An apparent inclination of the sweep lines to the vertical will arise when the cross-hair is not precisely horizontal.

It is evident from the optical nature of the cyclogram method of cycle analysis that there is a logarithmically decreasing exactness in assigning a cycle value with increasing length of the cycle. Hence, the abscissæ of the periodogram are taken to represent a logarithmically increasing range from 5 to 42; in practise a range of 5 per cent is used, successive intervals overlapping by one-half the range.

It is often of value to plot the individual cycle lengths in other ways than the one described above and called a cycle diagram. For instance, a long sequence of data may be segmented into several equal time intervals for each of which a cycleplot is prepared; if the sets of cycle lengths obtained by analysis are plotted in suitable symbols with the ordinates corresponding to the successive time segments equally spaced, then slant alignments from one segment to another may become evidence of cycle flow, *i.e.* gradual change of cycle lengths. Again, by using time on a vertical scale and cycle lengths as abscissæ (or the reverse), it is possible to represent graphically the exact range of occurrence of the cycles in any data. An example of this may be found in figure 31d where it is called a chrono-periodogram.

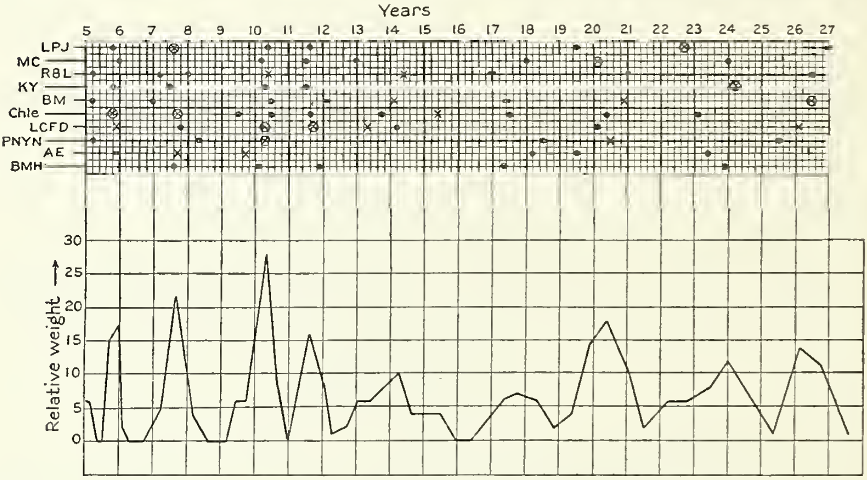


FIG. 57—Construction of a frequency periodogram from ten groups in the Central Pueblo area.

ERRORS OF THE INSTRUMENT

The errors of the instrument fall into two classes, those involved in the building of the cycleplot and those due to manipulation of the optical elements of the cyclograph.

Preparation of Curves—Measuring of specimens is now done almost exclusively with the standard measuring engine, a modification of the cathetometer method described in *Climatic Cycles and Tree Growth* (Douglass, 1919, pp. 58–59). A subordinate scale on the instrument checks decade sums and eliminates serious errors in measurement.

Many growth curves show trends due to aging of the tree, sudden favorable or unfavorable change in environmental factors and the like, which are meaningless in terms of cycles, and hence are removed by standardizing. This process is accomplished by transforming the actual measured values to percentage departures from a mean or standardizing line (run through the data by estimation) containing the trends it is felt should be removed. It has been found that standardizing lines drawn by Dr. Douglass when compared with lines through the same data drawn by the writer differ in only a small degree; however, it is evident that even a relatively large difference will have practically no effect on the lengths of the cycles found and only a small effect on the amplitudes. This is particularly true in light of the desirable practise of keeping the standardizing line as free from bends or "kinks" as the data permit.

Cutting Line—After a curve is smoothed, it is transferred by carbon tissue to a strip of brown opaque paper called cycleplot paper, some 48 inches long by 4 inches wide, and therefore slightly larger than the window of the cyclograph. A base line is then drawn on the curve; this is called a cutting line, and the maxima that it isolates are cut out with a razor blade. The present practise of the Laboratory is to use a cutting line that approaches or is a straight base line, usually parallel to the horizontal axis and at the approximate height of mean minimum. On the margins of a deep minimum, the straight cutting line is slightly modified downward, to avoid displacing the center of gravity of the maximum. Those minor maxima which lie below the cutting line are taken care of by cutting out only the very tops; those minima which lie above the cutting line are extended downward by means of narrow tongues. Tests show that cutting lines of different observers yield no definite difference as far as cycle lengths are concerned; the amplitudes of those cycles if determined optically from the cycleplot would, of course, be affected by cutting lines departing from the usual procedure. At present amplitudes are obtained by arithmetic summation of the data and are thus independent of the cutting line.

We may therefore conclude from a study of the errors in the cycleplot building process that, when the standard methods of the Laboratory are used, the resultant extraneous effects introduced into the derived cycle elements are too small to be of any consequence.

The most important of the errors involved in the actual manipulation of the instrument is the occasional slight change in the focus correction due to the convenient use of cords connecting the focusing device to the carriage on the track above. The practise in cycle analysis is, however, to test the calibration both before and after every analysis or short series, with the regular standard cycleplots, any scale error becoming immediately evident; the instrument is then adjusted, or if the error is small it is applied as a correction to the results.

Since the scale is calibrated in tenths of units, cycle values are at best correct only to the nearest tenth unit. In rare cases only, of outstanding cycles or in special study, is interpolation to hundredths of a unit made.

ERRORS IN CYCLOGRAM ANALYSIS

The matter of precision in assigning cycle lengths has received much attention. The material used consisted on the one hand of a large number of cycle analyses of the 42 Western Groups carried through by Dr. Douglass in 1926–28, and on the other hand of a considerable series on the same 42 Groups and also on the California Coast Redwoods made during 1933–34 by the writer. An intensive study of this material over a period of some months resulted in a set of statistical "constants" and is summarized in table 1.

TABLE 1—*Variations in cycle settings*

Tests	Cases	P. ct. Av. Diff.
1. Differences between Out and In Settings, same obser.		
(a) 42 Groups, unkn. scale, using Max. AED. Jan. 1928....	216	0.8
(b) 42 Groups, unkn. scale, using Min. AED. Jan. 1928....	271	1.0
2. Differences between two analyses of same material, same observer.		
(a) 42 Groups, using Max. 1st-direct; 2d-unkn. scale AED. 1926–8..........	190	2.4
(b) 42 Groups, using Min. 1st-direct; 2d-unkn. scale AED. 1926–8..........	178	2.5
(c) California Coast Redwoods, using Max. 1st-direct; 2d-unkn. scale. ES 1933..........	326	1.9
3. Differences between two analyses of same material, different observers.		
(a) 42 Groups (part), AED. vs. ES, principal cycles.......	46	2.5
(b) Same all cycles............	95	3.0
4. Effect of inverting curves for analysis.		
(a) 42 Groups, AED, 1st-Max; 2d-Min., Norm. Scale, 1926..	166	2.8
(b) 42 Groups, AED, 1st-Max; 2d-Min., Unkn. Scale, 1928...	241	2.0

1. Standard procedure in cyclograph use demands an analysis over the entire range not only when the mirrors are moved out, but also when they are brought in. As far as possible, the second analysis is made independently of the first. Some remembrance of the pattern may, however, influence the assignment of a horizontal setting the second time, in many cases, and for that reason differences were expected to be small.

As in the other cases discussed below, differences are chiefly due to confusion in the pattern because of weak cycles which make one setting hardly better than several others in the immediate vicinity. Sometimes only one or two dots (crests) will determine a significant alternative setting. When the pattern contains a strong cycle, alternative settings sometimes depend on the accepted duration of the cycle. Ambiguity arises in part also from the placing of emphasis on different portions of the cycle at different times. In many cases, two distinctly alternative settings may be made, only a portion of the individual dots being common to each. The average difference of these alternative settings was found in 31 cases to be about 5 or 6 per cent.

2. The second kind of difference is that resulting when the same material is subjected to analysis at two different times by the same observer. To make the test as rigorous as possible, the original analysis was compared with a second set in which the same data had been replotted on an unknown scale. Extensive analyses of this type in the 42 Western Groups by Dr. Douglass and in the California Coast Redwoods by the writer were available. After applying the proper correction factors to the second set, the average difference when using the maxima was almost exactly the same as that when the plots were inverted and the minima were used. The total number of cycle pairs compared was 694. An average difference of 2.5 per cent, the largest found, is not very great when we consider that we are dealing with highly variable phenomena containing fluctuations due to some minor extent at least to random causes.

TABLE 2—*Anomalous cycles*

Type of test (see table I)	Total cycle lengths, = y	Anomalous cycles, = x	P. ct. = 100 x/y
1a	507	75	15
1b	625	83	13
2a	506	126	25
2b	450	94	21
2c	841	191	23
3	250	60	24
4a	443	111	25
4b	665	183	28

3. The third kind of difference considered, that between two observers, is the most important. The only available data that could be used were in the 42 Groups; the analyses had been made some eight years apart and were, of course, quite independent. The average difference of 3 per cent is gratifyingly small; in this value there are included cycles, the identifications of some of which, as corresponding to the ones paired with, were highly doubtful. When only the strong cycles were used, the average difference is no larger than the difference of the second kind (see number 2 above).

4. In ordinary procedure the maxima of a curve are isolated for analysis. What happens when the minima are isolated instead? Comparison of analyses using maxima with those using minima shows that the average difference is of the same order as before. The total of 407 pairs of cycles is certainly large enough so that the result may be viewed with confidence. No apparent change was found in the number of emphasized cycles. There was also no evidence for any systematic increase or decrease in cycle length on inversion.

Frequently an observer finds weak cycles which another observer, or even the same observer at a different time, does not find. Such cycles (called anomalous and not included in our lists of weak cycles) constitute a serious matter for investigation. The amount of these cycles present are given in table 2.

It is significant to note that the out-in tests contain a much smaller percentage of anomalous cycles than the remaining kinds of tests; there is evidently a dependence of one set on the other, as suggested already. The similarity in the size of the remaining percentages indicates the absence of any systematic factor; but an average of one anomalous cycle in every four seems at first glance serious. It was found, however, that these are almost all weak cycles of little weight, and random length, which largely cancel out when the analyses in which they are found are summed into a periodogram.

Another question which may be considered here is the difference in the lengths of cycles analyzed at different times, as a possible function of the length of the cycle. The available data are summarized in table 3. When plotted there is evident a straight line relationship for each observer which may be expressed as

TABLE 3—*Cycle differences with cycle length*

Range — Years	No. of Cycles	Av. Diff. — Years	Obs.
5.1–10.0	112	0.173	ES
	77	0.195	AED
10.1–15.0	97	0.259	ES
	105	0.323	AED
15.1–20.0	45	0.336	ES
	76	0.389	AED
20.1–25.0	44	0.445	ES
	58	0.502	AED
25.0–and over	30	0.480	ES
	37	0.638	AED

$$\overline{\Delta n} = kn$$

where $\overline{\Delta n}$ = difference in cycle lengths.
k = constant for observer.
n = cycle length.

From the above table we find the differences in cycle values, in per cent, to be as follows:

Mean Cycle	Pct. Av. Diff. AED	Pct. Av. Diff. ES
7.5	2.6	2.3
12.5	2.6	2.1
17.5	2.2	1.9
22.5	2.2	2.0
29.5	2.2	1.6

The value of k is found to be 0.024 for AED and 0.020 for ES.

In summarizing this study of differences, we find that in spite of opportunities for disagreements the results of different observers are closely alike and we conclude that we are dealing with real cycle phenomena and a reliable method of analysis.

PROBABILITY TESTS

We now take up such matters as the tendency of an observer to favor certain cycle lengths (resulting in spurious emphasis on special values in the periodogram) and the recognition of real and unreal cycles. To investigate such problems by means of probability curves is illuminating.

A general method, used in the Tree-Ring Laboratory, for obtaining a lot-drawn or random curve is the following. Each year represented in a sequence of measurements of ring widths of a specimen or group to be used is marked on a slip of paper. All slips are then thoroughly mixed in a container, and drawn out at random without replacements. The values corresponding to the years drawn are put down in the order of drawing, and a curve is made from the series. This represents a quite accidental or probability arrangement, whose frequency distribution, however, is of course identical with that of the original curve. Each curve is then put into the cycleplot form.

Recognition Tests—A test was made with four 500-year lot-drawn curves, to which were added two 500-year real curves of northern Arizona tree-growth, and the analysis carried through by the rack method of simultaneous or concurrent analysis, every curve appearing for a moment in front of the cyclograph window and then giving place to its neighbor. Both real curves were recognized at once, by their evident similarity in the cyclograms.

A second and more extensive recognition test was made with a group comprising 27 lot drawings and 6 genuine curves. They received simultaneous analysis, five and six at a time, with two real curves for comparison; one was put in rack at the top, the other at the bottom, and the unknowns in between. The analysis was made in six sets. It is to be noted that the real curves among the unknowns were from the same geographic area (and hence contained approximately the same cycles) as the two comparison curves. Nevertheless, the results were quite gratifying:

Of 6 called genuine, 5 were genuine.
Of 2 called possibly genuine, 1 was genuine.
Of 25 called false, 25 were false.

We may conclude from this that when the curves are subjected to simultaneous analysis as above, the probability of picking out the real from the false is quite high.

Cycle Preference Tests—To test whether there was any preference in the matter of assigning particular cycle lengths and to test for characteristics of cycles in random sequences, a group was made up with considerable care consisting of 37 cycleplots of which 6 were genuine. All were individually analyzed without knowledge as to which were genuine and thus all received treatment as if they were real.

The periodogram values of the first 15 of the lot-drawn curves were compared with the values for the remaining 16. A correlation coefficient of 0.016 ± 0.117 was found, indicating completely random distribution of the cycles in lot-drawn curves. As a comparison, the periodogram numbers of the analyses of 22 dated Coast Redwood specimens were correlated with the numbers for 19 undated specimens. The correlation coefficient was 0.56 ± 0.08, strong evidence then that the cycles found are present in the trees concerned and not accidental in origin. The correlation coefficient for a similar comparison of the more homogeneous Central Pueblo Area curves was 0.76 ± 0.05. As a check, the correlation coefficient was obtained between the periodogram numbers representing analysis of two additional random groups. The value was 0.05 ± 0.11, again indicating random distribution of cycles in lot drawings.

THE PRESENTATION OF CYCLE DATA

In mass presentation of cycle data, as given in the lists of Chapter V, it is impossible to represent all the peculiarities of the individual cycles. The summation curves following this section supplement the lists but often do not reveal significant detail seen in the cyclogram. It is hoped that it will eventually be possible to publish cyclograms to accompany all cycles mentioned. The column titles in the tabular matter referred to are explained below.

Number—The numbers in this column refer to the summation curves (pp. 156). The latter are placed in order of increasing cycle length, which is the arrangement of the long chronology lists.

Cycle—This column gives the exact cycle length used in the amplitude computation. Since values of the cycle observed are subject to the inaccuracies already discussed, differences between two cycles of 2 to 3 per cent may not mean that they are different ones. For example, 13.6 and 13.8 may really represent the same cycle. Often a change in cycle length of 2 per cent or more will be found when the assigned duration is changed somewhat.

Occasionally a cycle is seen as two-crested, that is, with one set of subordinate intermediate maxima; the notation in the lists, *oc*$\frac{1}{2}$, follows the cycle length. Two subordinate crests are noted as *oc*$\frac{1}{3}$, and so on. If every other maximum in an alignment is especially strong, indicating the presence of the double-length cycle, it is noted in the lists as *x2* (times 2). This paragraph refers particularly to the cycle tables of the monthly sunspot numbers and the geological material.

Underlines—The significance of cycle underlines is discussed on page 146 and on page 147.

Duration—The dates just preceding the first maximum and following the last one were obtained at time of analysis. Dates were subsequently altered by as much as three or four years at beginning or end, to permit an integral number of rows in summation for amplitude. It is important to remember also that many cycles do not appear or disappear suddenly; hence caution is necessary in considering these dates as precise.

First Maximum—The position of first maximum as given is that of the highest part of the summation curve. Many cycles have two or more crests, non-symmetrical but often not widely different in height. It is evident that if one should force these curves into such artificial form as a sine curve with one crest, the position of maximum might be changed somewhat. It was felt that there was not sufficient justification for this final smoothing, and the summation curves were simply Hanned (Chapter II).

Rows—As stated above, usually only an integral number of rows or repetitions of the cycle were considered for amplitude. In a few cases of longer cycle lengths, half-rows were also permitted in order to make full use of the data.

Per cent Amplitude—The block method of summation for amplitudes, using for fractional periods rows not all containing exactly the same number of elements, has been discussed on pages 30 and 97. The difference between maximum and minimum of the Hanned summation curve is the total range of amplitude. Half this quantity, divided by the mean ordinate for the summation interval, is the per cent amplitude given. Here also, as in the case of the position of first maximum, further smoothing, and elimination of the effect of interfering cycles, might alter the results. It should be remembered that the summation method will yield the true amplitude only with an indefinitely large number of sets; the value obtained from the limited number of sets is an approximation.

A. D. Ratio—This test for cycle reality is discussed on pages 58 and 98. The values, while significant statistically, are not in themselves decisive for any individual case.

Vertical Scale—This refers to the summation curves: See discussion following.

CYCLE SUMMATION CURVES

The accompanying curves show the mean cycle forms derived in computing the amplitudes given in the tables of Chapter V. These curves become part of the reduction process and should be made clear to the reader, because the cycles may take forms quite different from the easy flow of the sine curve.

Identity of the curves will be recognized by the number attached to each curve which refers to a corresponding number given in the tables of Chapter V.

Exactly one cycle length is plotted and, if necessary, the curve is slightly smoothed by the usual Hanning process. In most curves the left end represents the date of beginning as indicated in the "duration" in the tables (the phase may be checked by referring to date of first maximum), and the horizontal scale is two years to the division. In the 5-year means it is, of course, 10 years per division. In laying out the curve for its repetitions the fractional year at its end, if any, must be taken into account.

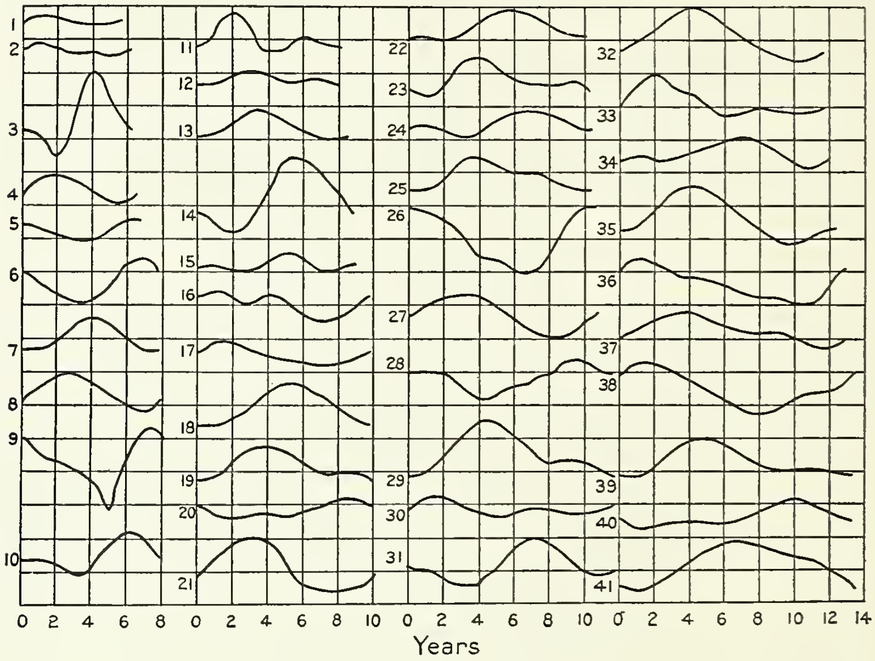
The ordinates in the summation curves are related to the data given in Vol. II, Appendix, in the following way:

$$M = \frac{R}{2\,AV}$$

where M = mean value of data in II used in amplitudes.
R = total range in summation curve, taken at 10 per cent change per division.
A = per cent amplitude in tables.
V = vertical scale value in tables; a value of unity being taken where no entry is made in that column.

For SVI cycles, M will give the actual mean ring size. Data for the 42 groups and CPC were largely standardized and some groups were measured in different units. For comparison purposes it might be added that the approximate mean ring size in the 42 groups as a whole is 1.35 mm. It is proposed to publish the mean ring sizes in a forthcoming article.

42 Western Groups



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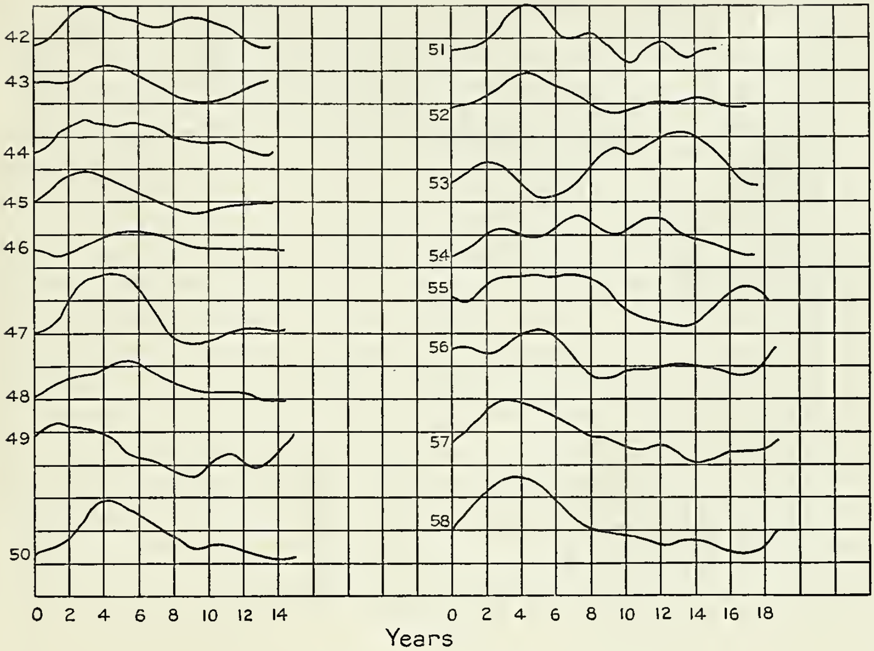

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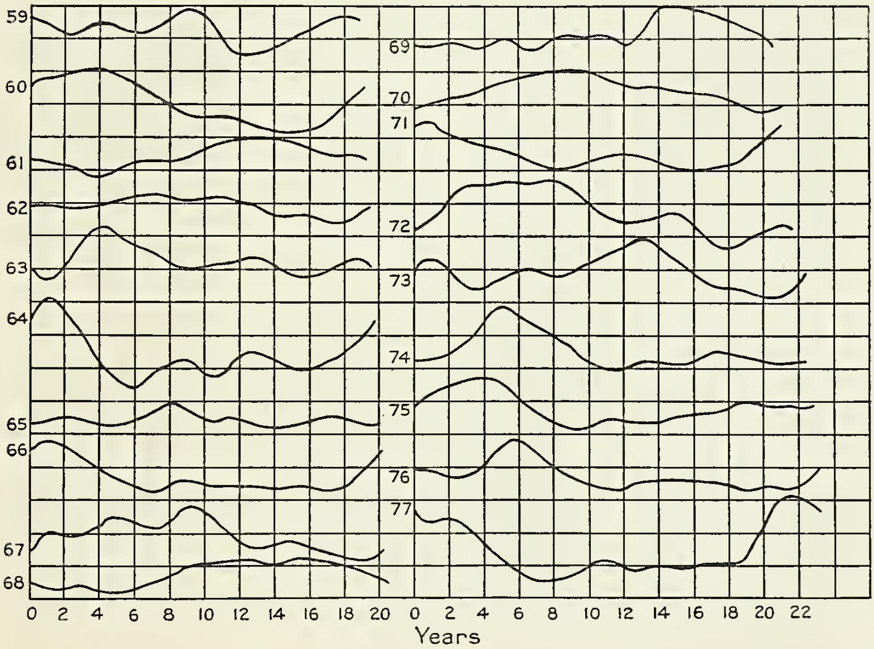

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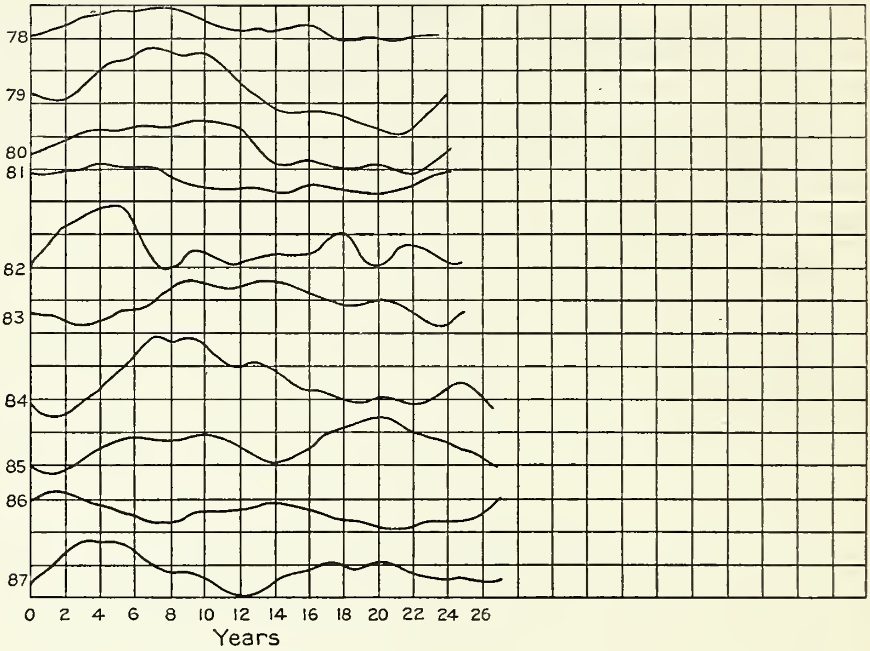

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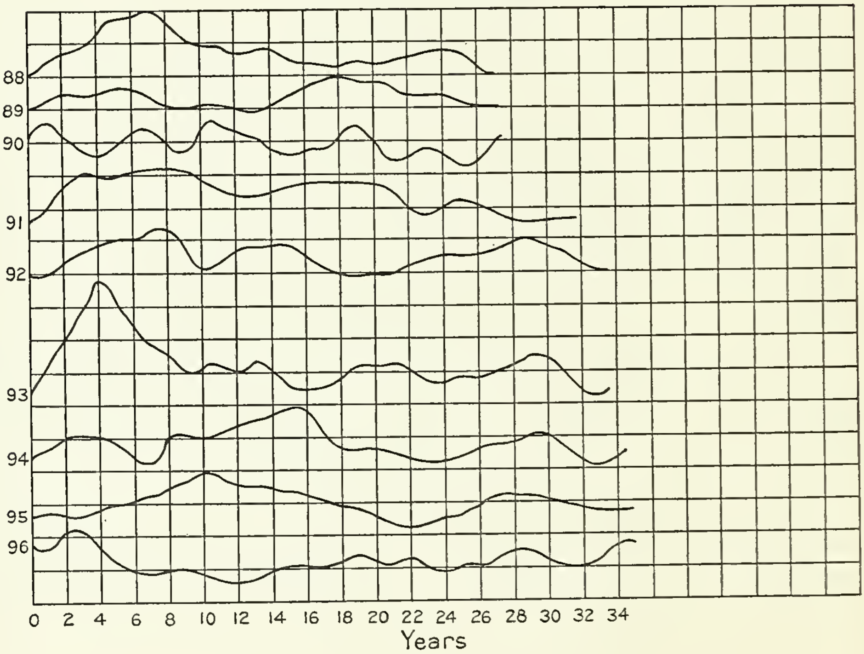

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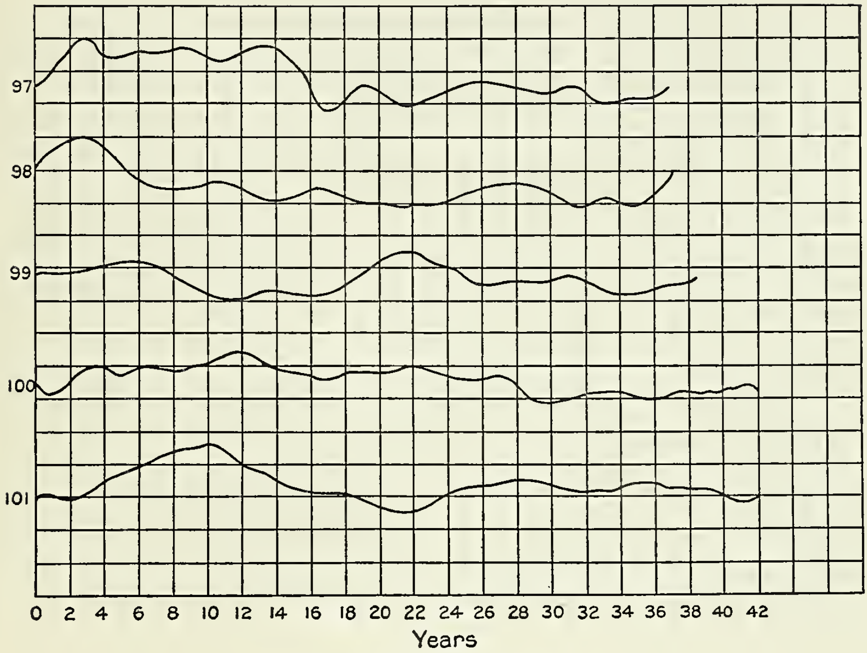

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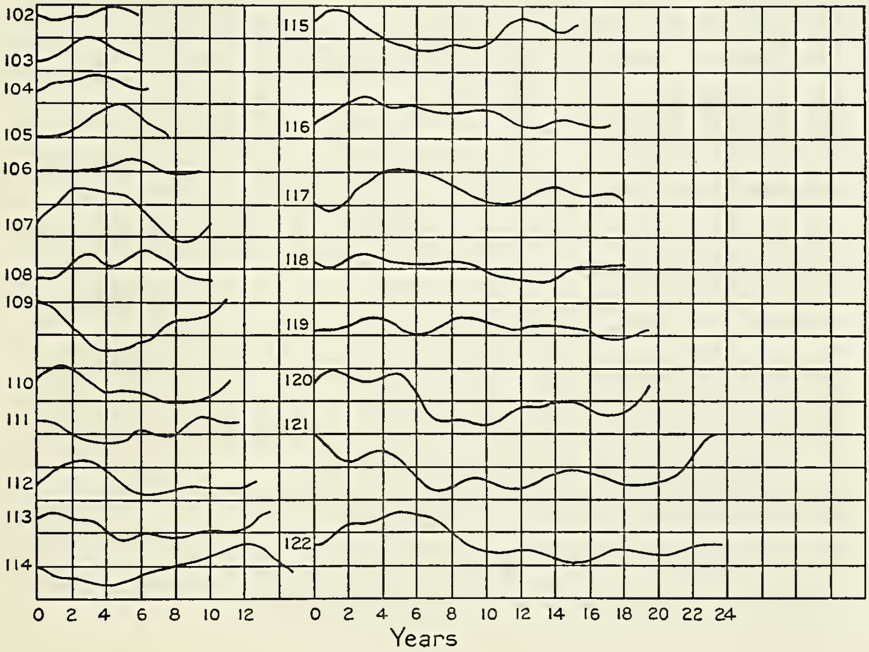

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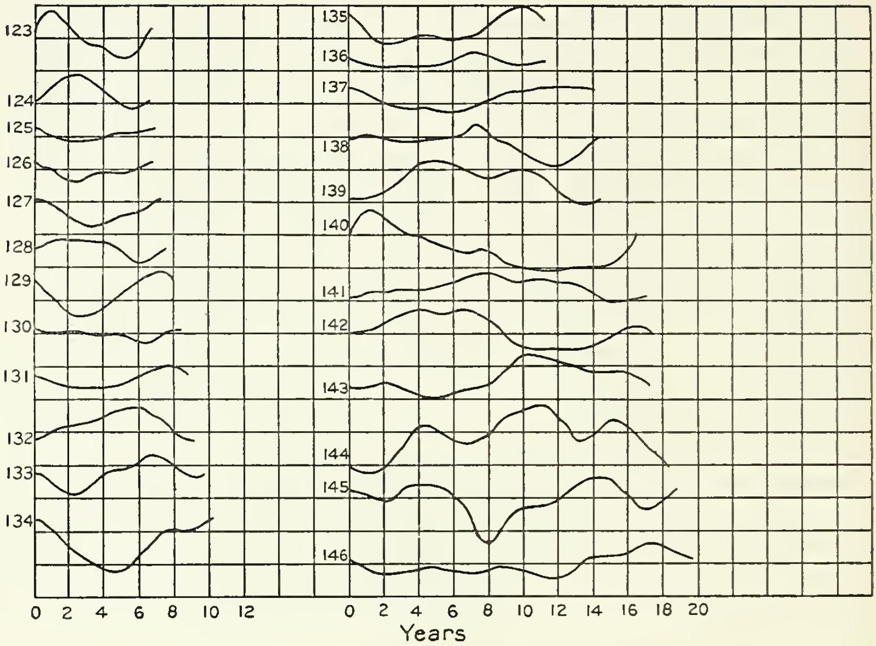
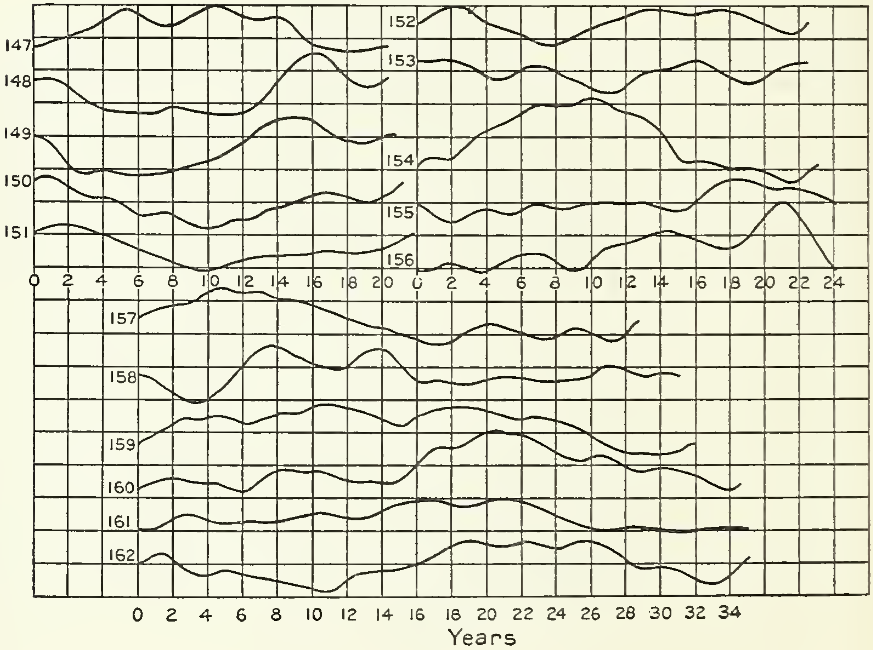
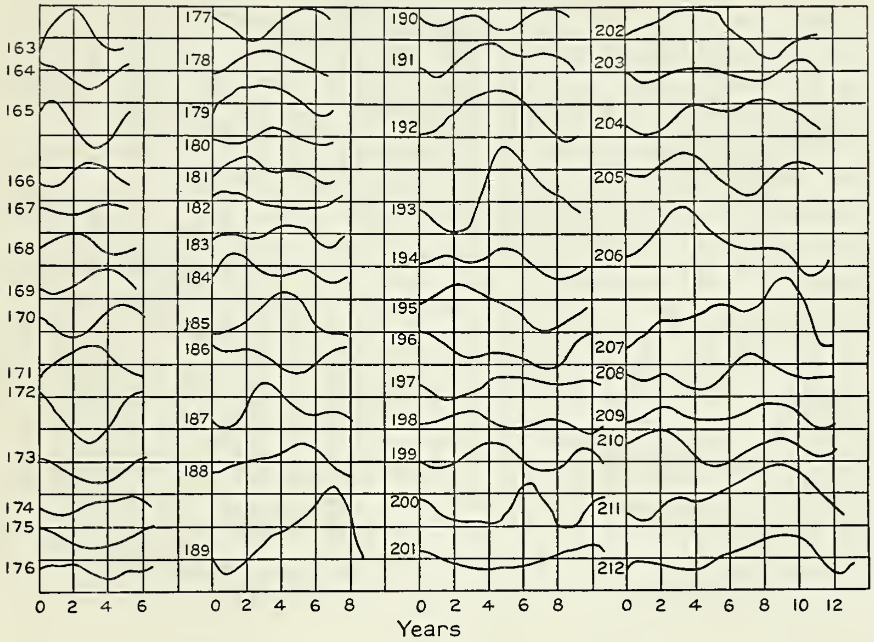


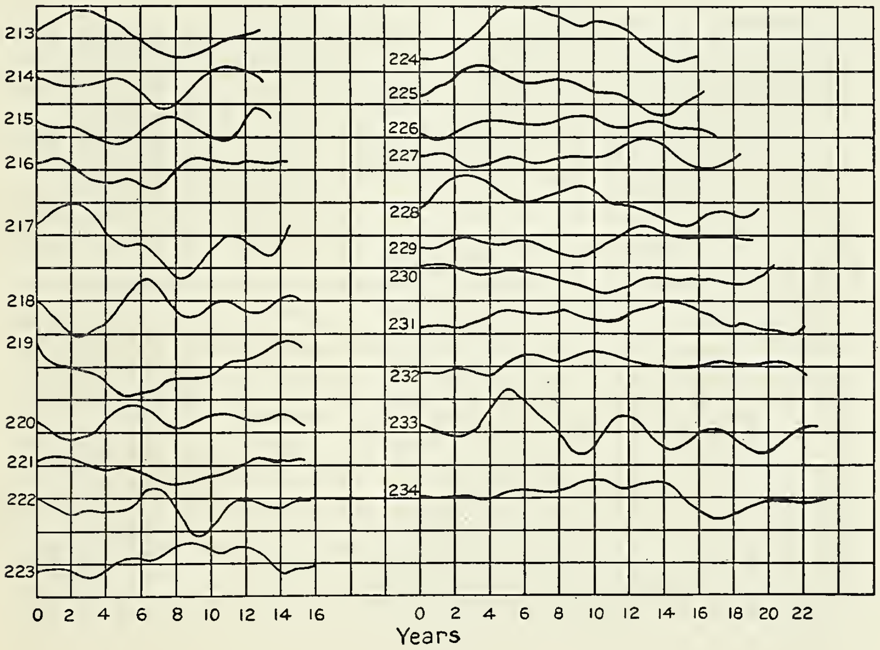
42 Western Groups



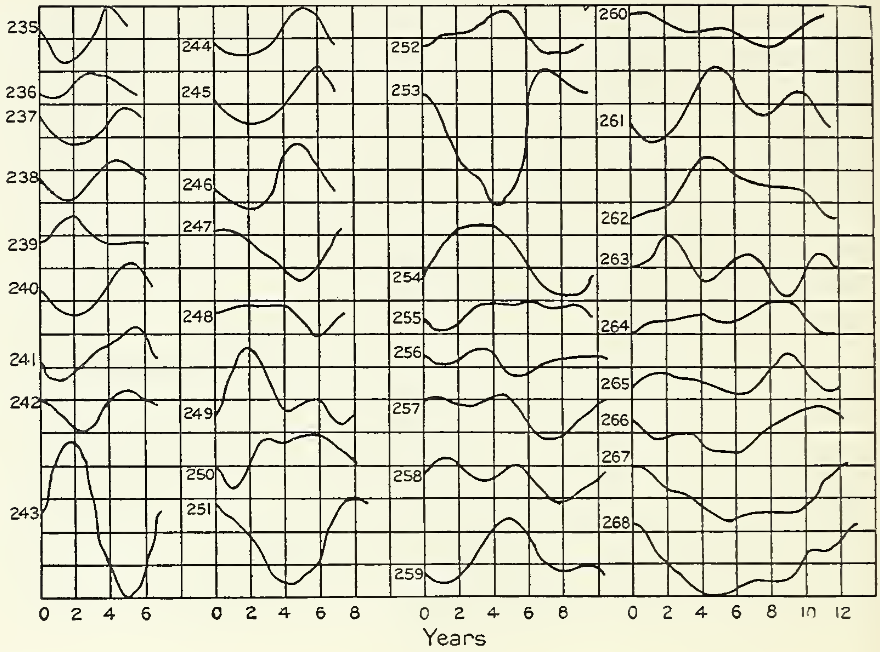
Sequoia Chronology



Sequoia Chronology



Central Pueblo Chronology



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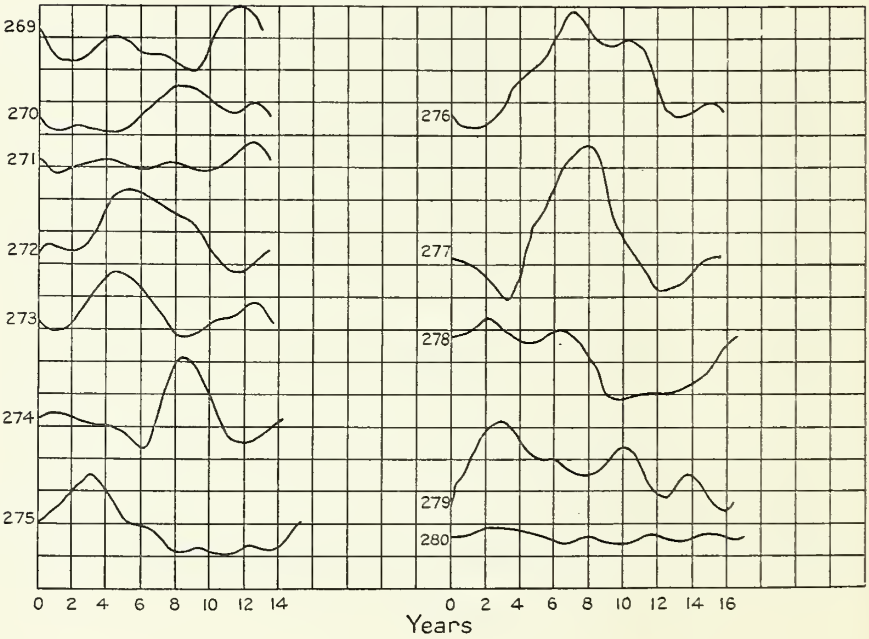

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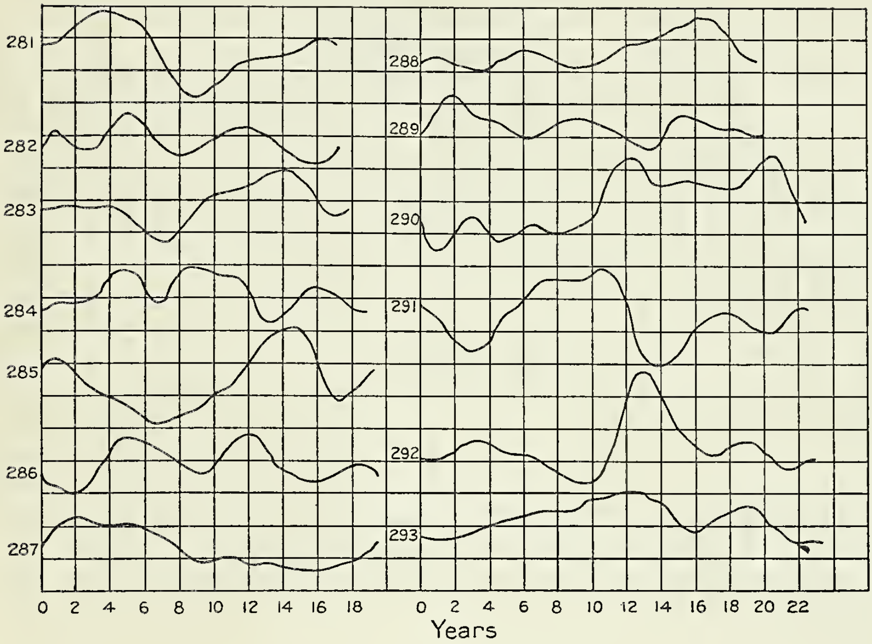

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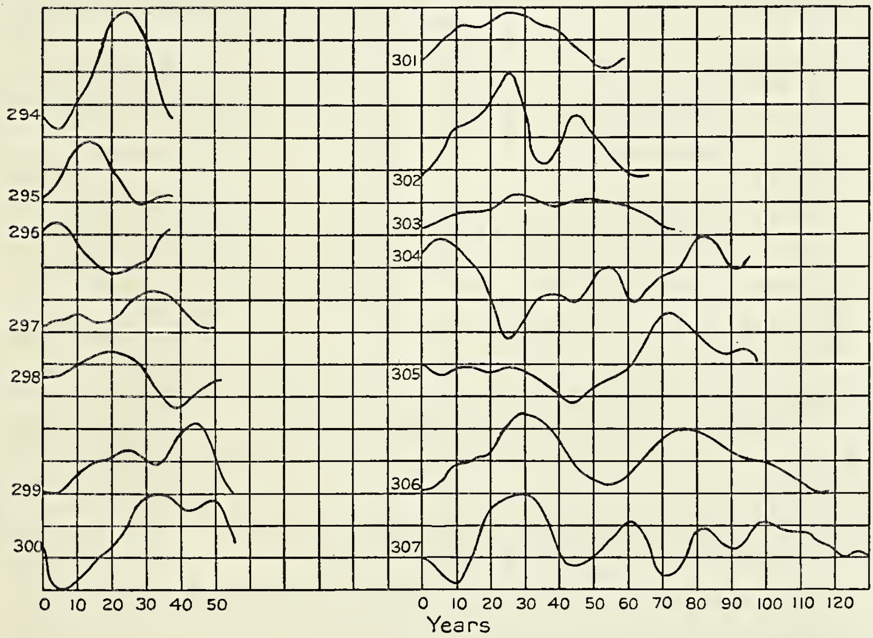

AN AUTOMATIC OPTICAL PERIODOGRAPH[1]

VARIABLE STAR TESTS

In all the previous work which had been done with the periodograph, a continuous series of observations was used. The test of discontinuous observations was made on variable stars. In order to avoid prejudices and to get a fair sample of variable stars, my assistant selected a certain number from the table given in volume 37, in the Annals of the Harvard College Observatory, page 202. They comprised the 10th, 20th, and 30th star, etc., in the list. The accompanying table will give the results of the test and the time taken to obtain each one. One must remember, of course, that this was the first application of that instrument to these interrupted periods, and one can say confidently that the average time to solve a variable star period (after the plot is made) would be five or ten minutes. The columns in this table marked "Curve Period" and "Computed Period" are from Harvard Observatory Annals, volume 57, page 182. The "Curve Period" was obtained directly from a plot. The "Computed Period" was obtained after an application of the method of least squares. It is seen that the periodograph results agree very well with the least square solution. The solution of X Virginis, as seen in the table, was obtained after a very long study. The period of 52 days seems applicable if the observations of J. D., '2815, are omitted.

Number	Name	H.C.O.ANN. 57:182		Periodograph Period Days	Time taken to reach solution
		Curve Period Days	Computed Period Days		
R	021024 R Arietis	181.7	186.6	186±1	19 m.
V-1	042309 S Tauri	392.5	365.0	186±1 372±2	52 m.
V-2	115609 X Virginis	(No solution)		52 omitting 2815 J.D.	4 h. 35m.
V-3	134440 R Can. Ven.	317.2	333.0	332±3	34 m.
V-4	163137 W Herculis	287.0	280.2	282±2	45 m.
V-5	201647 U Cygni	470.9	461.3	463±3	43 m.

The method by which the solution was obtained consisted in placing a strip of slightly tinted yellow glass behind the minima of the curve in which all the observations were plotted by their distance from a mean line. This made a mixture of yellow and white spots on the differential pattern. When this mixture of spots resolved itself into alternate yellow and white rows, then a period was indicated. This could be done very readily. In the periodogram the alternate beads or corrugations come down in different colors. Such a periodogram of R Arietis is shown in Plate 12b.[2] The marginal marks in this figure correspond to a period of 150 days, 160 days, etc. There are two places in the figure where the corrugations are especially evident; one had about 157 and the other had about 187 days. In the instrument the latter is immediately recognized as the true period, because the lines are alternately yellow and white.

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[1] Presented at astronomical meetings, Pasadena, June 20, 1919, and Ann Arbor, September 3, 1919. See abstract in Pub. Ast. Soc. Pac., Vol. XXXI, 188, June 1919. Introduction omitted here.

[2] The reference to plates applies to this book but the photographs here are reproductions from the original article.

Plate 24 shows a differential pattern of SS Cygni, so taken that vertical lines of dots show a period of about 110 days. The predominant periods may easily be worked out from this diagram. For the first four years, beginning about 1896 the double-crested 117-day period was the most prominent. Then for six years a double-crested asymmetrical period of 107 days was the most prominent. Then there was nearly a year of readjustment followed by two years of 110-day double-crested periods. This was followed by three years of 125-day double-crested periods, returning finally to four years of 117-day double-crested asymmetrical periods. This alignment of dots is best seen by looking at the figure from a low angle rather than from the perpendicular position of ordinary reading.[1]

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[1] In considering this pattern eighteen years after it was first made and comparing it with cyclograms of solar records and of climatic data, we note that it shows the type of persistence, of bisection and of somewhat irregular changes that appear, for example, in the magnetic character figure C. In this analogy we have a suggestion that this type of variation might have its origin in the rotation periods of a large body like our sun.

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